Open Pit Mining & The Cost of Water
Potential Opportunities Towards Sustainable Mining

by

Sébastien J.R. Fortin, P.Eng.
B.A.Sc., Laval University, 1996
M.Sc., Laval University, 1999
GDBA, Simon Fraser University, 2011

PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF BUSINESS ADMINISTRATION

In the Executive Master of Business & Administration Program
of the
Faculty
of
Business Administration

SIMON FRASER UNIVERSITY

Spring 2015

Approval

Name: **Sébastien Fortin**

Degree: **Master of Business Administration**

Title of Project: **Open Pit Mining & The Cost of Water**
Potential Opportunities Towards Sustainable Mining

.

Supervisory Committee:

Elicia Maine, PhD
Senior Supervisor
Associate Professor, Technology Management & Strategy
Academic Chair, Science & Technology Commercialization
Beedie School of Business, Simon Fraser University

Ian McCarthy, B.Eng, M.Sc., Ph.D. C.Eng., IMechE.
Second Reader
Associate Dean, Graduate Programs
Professor, Technology and Operations Management / Strategy

Date Approved: June 30th, 2015

Abstract

Mining operations require vast quantities of water to run ore processing facilities and thus have a responsibility to manage this critical resource. Operations are often located in areas of limited water supply, which may create a competitive climate for water consumption. Make-up water for mineral processing can represent a significant portion of production cost for mining companies. While necessary for mining, water in open pits is problematic for extraction activities and leads to increased operational and maintenance costs.

This paper analyses the operational and financial impacts of water at three copper mines. Potential options to improve reclaim and pit dewatering volumes are evaluated with the objective to reduce operational costs and water losses. The evaluation of these options integrates Teck's sustainability strategy and considers water regulations currently changing in Canada and Chile. This paper concludes with the advantages of maximizing open pit dewatering to reduce make-up water requirements, and thus reduce mining production costs.

Keywords: mining; water; sustainability; dewatering; tailings facilities

Executive Summary

Water is both a resource and a responsibility for the mining industry. The ore extraction process requires large amounts of water to supply the plant facility. From this perspective, mining companies needs to consider and minimize the impact on surrounding communities and ensure the resource remains available in the future. As a paradox, the presence of water in an open pit mining environment can create significant operational issues to mining activities and can lead to increased mining costs. This project considers two open pit copper mines (Highland Valley Copper, BC and Carmen de Andacollo, Chile) and one brownfield project (Quebrada Blanca Phase 2) operated by Teck Resources Limited with the objectives to:

i. evaluate the financial impact of “wet mining”;

ii. determine and compare the cost of process and make-up water at the plant; and

iii. identify options to reduce the financial impact of water in mining, which are consistent with Teck’s sustainability strategy.

The new Water Sustainability Act currently under review by the government of British Columbia proposes to regulate the use of both surface and groundwater in the province, and to install a user-payer system for consumption of water as a provincial resource. These regulatory changes will financially affect the Highland Valley Copper (HVC) mine as it obtains approximately 17% of make-up water from pit dewatering activities. Similarly, the *Direccion Regionale del Agua* (DGA) is also review groundwater extraction rights from the Elqui River valley, where Carmen de Andacollo mine (CdA) obtains its make-up water. These regulatory changes represent a threat relative to the availability and the unit cost ($\$/m^3$) of make-up water for these operations.

The presence of groundwater in all three active pits of the HVC mine creates “wet mining” conditions, which negatively influence mining operations. These impacts include increased costs for drilling and blasting activities due to wet holes, inefficiencies for truck haulage due to wet ore and consequently increased diesel fuel consumption, and increased maintenance costs associated with tires and equipment wear. The cumulative annual costs incurred by “wet mining” are estimated at over $8M/year for HVC. Not accounting for

advantages in pit slope design and stability advantages that could ensue from increased dewatering, this analysis clearly demonstrates that further dewatering is both needed and financially justified to reduce the mining unit costs. Future pit dewatering activities at THVC should ideally focus on the pit rims to minimize energy requirements and infrastructure costs for extracting the groundwater. The added benefit of enhanced dewatering at HVC would be to further increase the pit-dewatering component of make-up water in order to avoid operating the Spatsum Booster station at the Thompson River; this water is more expensive than dewatering water ($0.57/m^3 versus $0.38/m^3).

A gap analysis was carried out to evaluate options to reduce either the unit cost of water or the operational impacts of water in the mine, or both. For HVC, the reclaim rate from the LL-dam tailings storage facility (TSF) is over 80%, i.e. at the upper range of the industry average. The make-up water for the process plant largely comes from pit dewatering activities (over 90%, representing over 17% of total water), with sporadic input from the Spatsum station. In comparison, the CdA mine shows a reclaim rate of about 74% and obtains only 4% of process water from pit dewatering activities; pit dewatering represents about 15% of make-up. Consequently, the unit consumption rate of make-up water for CdA is around 0.52m^3/T copper produced, compared to 0.28m^3/T for HVC. The main source of make-up water for CdA comes from the Elqui River valley, at a unit cost of approximately $1.44/m^3 mainly related to high energy costs for pumping the water to the process plant.

Two options were identified as potential sources of local, cheaper make-up water for CdA. A recent groundwater flow model indicates that pit dewatering extraction rates could be doubled from 60L/s to ~120L/s. Although the installation of about six additional wells and associated infrastructure would require investment of over $1.2M, the annual savings are estimated at over $1M/year. In addition, the collection of fog water from mountain hillsides below the town of Andacollo offers another modest source of water. This preliminary analysis suggests that an investment of approximately $1M to construct a 20hectare fog water collection system could produce some 100,000m^3/year of water, representing a reduction of 1% of make-up water with associated annual savings of approximately $150,000. This option is primarily interesting from a sustainability aspect when considering the involvement of the communities.

The installation of a floating solar plant was identified as a highly interesting and beneficial option for CdA, which could significantly reduce pond evaporation, and hence make-up water requirement volumes. Reclaim water unit cost for CdA is estimated at $0.91/m^3 compared to $1.44/m^3 for make-up. In addition, the solar plant could potentially produce sustainable electricity at a competitive price, which is aligned with Teck's energy reduction strategy. At a preliminary level, this option would represent capital investment of $30-40M. A similar, albeit smaller system was recently commissioned in South Australia in 2014.

For QB2, the predicted reclaim rate from the TSF is only about 40%. Pit dewatering cannot provide groundwater in sufficient quantities to materially contribute to the make-up water balance. Consequently, the only source of make-up water for the project is desalinated water, which represents a unit cost of $2.36/m^3. The unit consumption rate for make-up water of 0.63m^3/T copper produced ranks this project at the higher end of consumers for northern Chile. The high unit cost of water is mainly attributed to the large energy requirement for pumping the seawater to the mine. The construction of a large solar panel plant to offset the high electrical cost from the grid was the only option identified that could potentially reduce water costs.

In conclusion, the water required for the ore processing plant can represent up to 5-10% of the total production cost per pound of copper produced; water is an expensive commodity. "Wet mining" can also significantly increase operating costs in the mine. It is recommended for Teck to better quantify the cost of water across the water balance for each site, and to further evaluate the financial implications of water. The industry in general needs to appreciate the cost of water in mining, beyond the sustainability implications. This study recommends Teck to further investigate, identify and implement water management strategies and technologies to conserve this critical resource and minimize costs to remain competitive. The above-mentioned options could assist Teck to turn risks into opportunities.

This paper in no way reflects the thoughts or intentions of Teck. The ideas explored within the paper are those of the author only, and are not in any way binding upon Teck or anyone else. Any error in interpretation or facts falls squarely on my shoulders.

Dedication

This paper is dedicated to my family; your help and encouragement sustained me through both this project and the program.

To my mother Murielle Fortin, who has always believed and ingrained in me the importance of learning and the virtue of discipline.

To my beloved children Zachary, Juliana and Raphaelle. I will remember all these early mornings and late nights and travels. Promises made are promises kept!

And above all, to my dearest wife Magalie Levasseur, for her fortitude and self-sacrifice. How I admire you. I am blessed to have you as a partner. Thank you for making so many things possible in life. I love you!

Acknowledgements

Firstly, I would like to thank Teck Resources Limited for supporting this EMBA program through Simon Fraser University. Also thank you to Mr. Chris Dechert for acting as my corporate sponsor. A further note of appreciation goes to Mr. Greg Brouwer for allowing me flexibility when it mattered most.

I reached out to a number of busy people to obtain the data necessary for this project. As such, I also want to warmly thank Mr. Paul Dixon, Mr. Chris Fleming and Mr. David Adema from HVC, Mr. Juan Carlos Gomez from CdA and Mr. Troy Jones from the Teck Vancouver office. Special thanks to Mr. Geoff Beale from Schlumberger Water Services for his patience, enthusiasm and friendship.

I wish to express my sincere gratitude to Dr. Elicia Maine and Dr. Ian McCarthy for the sustained guidance, encouragement and feedback on this project.

Special heartfelt thanks and congratulations to my fellow Teck colleagues, who continuously and diligently worked to complete this program. It has been a pleasure to know you, and learn from you. I wish you all the best for your future endeavours.

Finally, my most loving recognition to Magalie Levasseur for her unconditional help. I will owe you forever, and beyond!

Table of Contents

List of Figures

List of Tables

Glossary

AMSA	Antofagasta Minerals Ltd.
BCME	British Columbia Ministry of Environment
BCMMPR	British Columbia Ministry of Minerals and Petroleum Resources
BU	Business unit
CAPEX	Capital expenditure/cost
CBU	Copper Business Unit
CdA	Carmen de Andacollo mine
COCHILCO	*Corporacion Chilena de Cobre*
COI	Community of Interest
CONAF	*Corporación Nacional de Forestación*
DGA	*Dirección Genérale del Agua*
DOH	*Dirección de Obras Hydraulicas*
GRB	Geotechnical Review Board
HVC	Highland Valley Copper mine
IWMP	Integrated Water Management Plan
LFC	Large fog collector
LOM	Life of mine
MASL	Meters above sea level
MGT	Million Gallon Tank
OPEX	Operating expenditure/cost
QB	Quebrada Blanca mine
QB2	Quebrada Blanca Phase 2 project
RO	Reverse osmosis
SEIA	Social and Environmental Impact Assessment
SWOT	Strength-Weakness-Opportunity-Threat
THVC	Teck Highland Valley Copper mine
TPOH	Tonnes per operating hour
TSF	Tailings Storage Facility
USGPM	US gallons per minute.
WBPH	Witches Brook Pump House

1: Introduction

This paper examines the operating cost impacts of "wet mining" at Teck Resources Limited (Teck) and the costs related to process water supply in the context of corporate sustainability strategy. The analysis presents and quantifies the challenges faced by the mining industry and proposes a lower cost mine dewatering and water reclaim strategy towards sustainable mining. The intent is to investigate the value-added potential of increasing dewatering activities (i.e. reducing operational inefficiencies related to excess water in the pits while increasing the pit's contribution to process make-up water) and to make recommendations for Teck.

1.1 Teck's Copper Business Unit

Teck is the largest diversified Canadian mining company. The company is committed to responsible mining and mineral development with major business units (BU) focused on copper, steelmaking coal, zinc and energy. Teck is a significant producer of copper globally, and ranks among the top ten producers in the Americas, with five operating mines and large development projects in Canada and South America.

Copper accounted for 41% the company's business in 2014, with 330,000 tonnes produced at the five copper mines: Quebrada Blanca (QB) and Carmen de Andacollo (CdA) in Chile; Antamina in Peru; and Highland Valley Copper (HVC) and Duck Pond in Canada (Teck, 2015d). With the exception of Duck Pond, these operations are open pit mines that use a traditional flotation circuit to produce a copper concentrate. Only the QB mine QB uses a solvent-extraction electro-winning (SXEW) to produce cathodes.

Teck is presently advancing a few development projects to enhance the copper BU portfolio of long-life copper resources, including the Quebrada Blanca Phase 2 (QB2) and Relincho projects in Chile, and Galore Creek project in northern British Columbia. Both a Feasibility level and Social Environmental Impact Assessment (SEIA) studies are currently being completed for the QB2 project. In addition, Teck is actively exploring and assessing development opportunities for new copper deposits in Canada, Chile, Mexico, the United States, Namibia, Peru, Turkey and Australia (www.teck.com).

1.2 Open Pit Mining & Water Resource

Water is a fundamental resource for life. Whether from surface or groundwater sources, availability to water that meets quality and quantity requirements is a critical need worldwide. The mining industry must share the responsibility for meeting this need now and in the future (ICMM, 2012).

Water is used in mining within a broad range of activities including mineral processing, slurry transport, construction, dust control, environmental mitigation, etc. Over the last several decades, the industry has made progress in developing closed-circuit approaches that aim to reduce water losses and maximize water conservation. Nevertheless, recirculation rates for these systems vary across a broad range and the vast majority of open pit mine operations rely on outsides sources to supply water to the ore processing facility. At the same time, mine operations are often located in areas where there is significant competition for water with municipal, agricultural and industrial demands, and there may be different perspectives and cultures on the priority for the available water. These characteristics together lead to tough challenges and there is no simple recipe for water management in mining, especially given the fact that the mining environments range from deserts to high rainfall tropical environments. Regardless, responsible management of water by mining companies is a key ingredient in ensuring a positive contribution to sustainable development over the long-term.

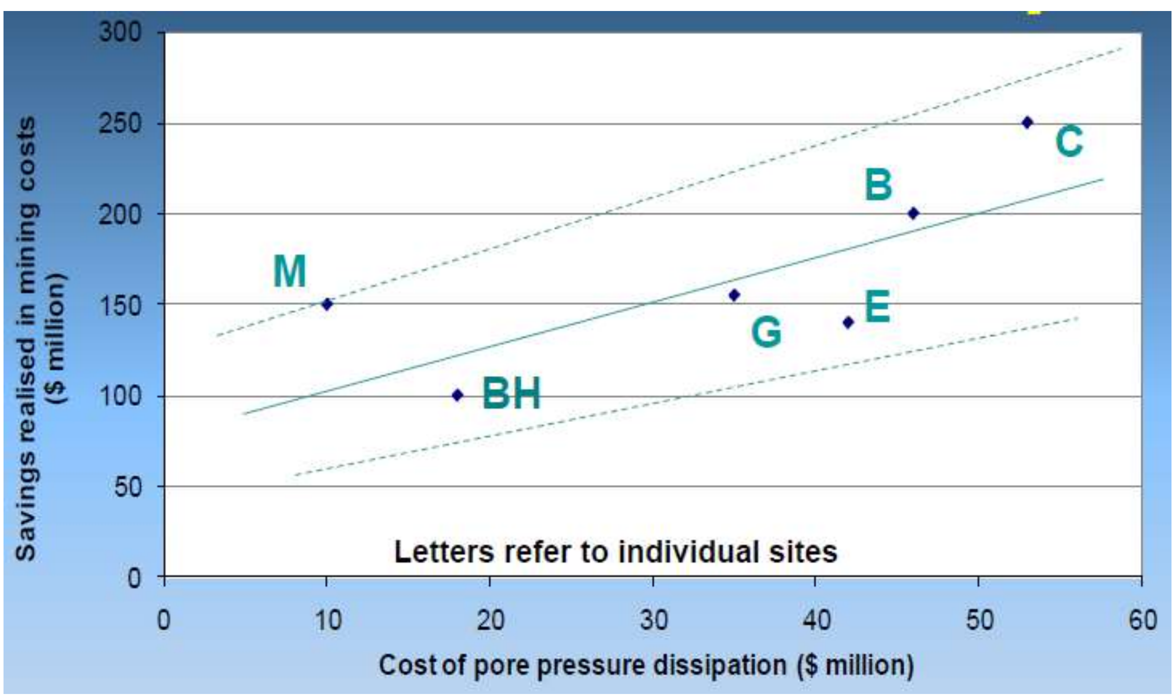
For instance, Carmen de Andacollo Operations, the Relincho resource development project, and Quebrada Blanca Operations and its associated Phase 2 project are located in water-stressed regions where the fair allocation of water is essential (Teck, 2013). Demand for water in these regions may result in water resources becoming unavailable or more costly to utilize. This could increase operating and capital costs for water supply, or result in community concerns. Water scarcity can also lead to increased regulation and reduced water rights for mining companies. The opposite can also be problematic, i.e. some mines can have an “excess” of water. .

Most open pit mines encounter some amounts of water at some point during the mine’s life, which generally is detrimental to mine operation activities. Pit slope stability in vulnerable zones intimately depends on some depressurization effort and minimizing recharge in these areas. Pit dewatering is typically executed with the objective of reducing water inflow “only” to a degree to support mining operations. Figure 1-1 illustrates the operational issues typically related to the presence of groundwater in open pit mines . These operational impacts can have substantial financial consequences for an open pit mine, which is discussed in Section 3. Several mines opt to control these impacts with active pit slopes dewatering systems. The investment in mine dewatering can be significant, but incurred benefits can also be substantial as shown on Figure 1-2 (Beale, 2011).

Figure 1-1: Typical impacts of groundwater seepage creating wet operating conditions in open pit mining.

(Courtesy SWS, J. Downing, 2011)

Figure 1-2: Relative financial benefits of dewatering for various pushbacks in large open pits.



(Courtesy SWS, G. Beale, 2011)

1.3 Regulatory Framework

Laws regulating water vary around the world, but generally speaking the mining sector can expect to be increasingly required to demonstrate a leadership approach to water use and management (ICMM, 2012). As water plays an essential role in the mining process, responsible water use is a critical business issue that affects the ability of individual mines to establish, operate and close. In this regards, Teck's vision on water is nicely summarized in an online video found at: http://www.tecksustainability.com/sites/base/pages/our-strategy/water.

In Canada, the extraction and usage of water is regulated at the provincial and federal levels via permits and licenses, which are primaly based on the Canada Water Act. Water permits dictate both how much water a mine operation can withdraw from any given source (i.e. pumping rates, net volumes, extraction periods, etc.) as well as how much mine water (process-impacted or other types) can be discharged to a surface or underground water body. This later aspect involves a material stewarship component to mine water management, which is another Teck sustainability objectives. As an example, consider the potential run-off or discharge of water coming from the open pit which can carry ammonium nitrate originating from rock blasting activities as a result of emulsion washing out. The excessive release of nitrate into a water course can generate the growth of algaes that can degrade the water course and impact aquatic fauna.

In most jurisdictions, water permits are scrutized by regulatory agencies through regular site inspections and periodic data reviews. In attempt to be proactive and show transpacency, in 2013, each Teck operation completed integrated water management plans (IWMPs) that describe how water will be managed at the sites (Teck, 2015a, 2015b). This clearly shows the intent of some mining companies towards responsible water management. However, the initiative is still young. One way to advance the benefits of IWMPs at Teck is to consider the financial implications of water in the mining environment, for instance to compare the cost of "doing it" versus "not doing it". It is an objective of this paper to provide a preliminary basis for such a comparative assessment.

One of the challenges that BC mining companies will face in the future is the new Water Sustainability Act that the government is currently finalizing (BCME, 2014). Currently under revision, it will replace the old BC Water Act, which only vaguely provided regulations for surface water use. The new act proposes to license groundwater, whereas historically only the wells themselves were regulated. While the actual volume of groundwater use has not been regulated thus far, the new act proposes to include a fee for water consumption. Historically, BC companies were charged for surface water use. In future, groundwater extraction will also be metered and charged to mining companies as use of a provincial resource. Table 1-1 provides a simplified overview of the overarching regulatory framework controlling water management activities for mining companies operating in British Columbia, such as Teck.

Interestingly, the regulatory framework for freshwater usage is strikingly similar in Chile, where Teck also operates. The legal requirements around the water resource are based on a combination of federal and regional (*sectorial*) legislations. Fundamentally, the 1980 Constitution of the Republic of Chile guarantees citizens the right to live in an environment free of contaminant. Furthermore, Article 19 No. 8 states that the Constitution ensures that it is the duty of the state to defend this right is not affected and to protect the conservation of nature. Chile federal Law no. 19.300 presents the general basis for all environmental regulations in the country. The 1981 Water Code (*Codigo del Agua*) is the particular legal instrument that regulates freshwater usage in Chile. Under this code, water permits are issed at the federal level through a process of public consultation in the regions (I to X) where a mine operates. The regions also administer the water rights issued to private companies for water extraction.

The *Dirección General de Aguas* (DGA) is the public organism responsible for the management of the water resource through the use regulations, monitoring and audits. In parallel, the *Dirección de Obras Hidráulicas* (DOH) is the public organism whose mission is to regulate the hydraulic infrastructure that allows the optimum water supply to communities. Therefore, any mining operation whose activity involves the use of water would inherently deal with these organisms.

Table 1-1: Regulatory framework controlling water activities in British Columbia.

	Driver	Description
Canada Federal Regulations	Canada Water Act	Provides for the cooperative management of water resources and water quality
	Canadian Dam Association	Dam safety guidelines
	Canadian Environmental Protection Act	Guidance for sustainable development
	Department of Environment Act	Establishes the federal Department of Environment and assigns leadership of it to the Minister of Environment
	Fisheries Act	Management and protection of fisheries resources
	Metal Mining Effluent Regulations	Regulation of tailings and other mine wastes deposition *(developed under the Fisheries Act)*
	Mining Association of Canada (MAC) Towards Sustainable Mining (TSM) Performance Indicators	Tailings and Water Management Assessment Protocol
	Navigable Waters Protection Act	Regulation of interferences to navigation on navigable waters
British Columbia Provincial Regulations	Drinking Water Protection Act	Regulation of water supply systems and protection of supplies
	Drinking Water Protection Regulation	Requirements for drinking water quality (*developed under the Drinking Water Protection Act*)
	Environmental Assessment Act	Establishes an assessment and certification process performed by the province prior to major projects
	Environmental Management Act	Management of the quality of land, water, and air
	Fish Protection Act	Provides legislative authority for water managers to consider impacts on fish and fish habitats
	Mines Act	Requirements to initiate, operate, and abandon/reclaim a mine
	Water Act (current)	Allocation and management of surface and ground water
	BC Water Sustainability Act (to replace Water Act in 2015)	Modernization of the Water Act proposed to better meet needs of all stakeholders
	British Columbia Dam Safety Regulation	Obligations of owners to safely design, operate, and maintain dams (*developed under the Water Act*)
	Ground Water Protection Regulation	Regulation of wells (*developed under the Water Act*)
	Water Regulation	Management of and payment for water rights (*developed under the Water Act*)
	Water Protection Act	Prohibits bulk export or transfer of water

(Adapted from Teck, 2015b)

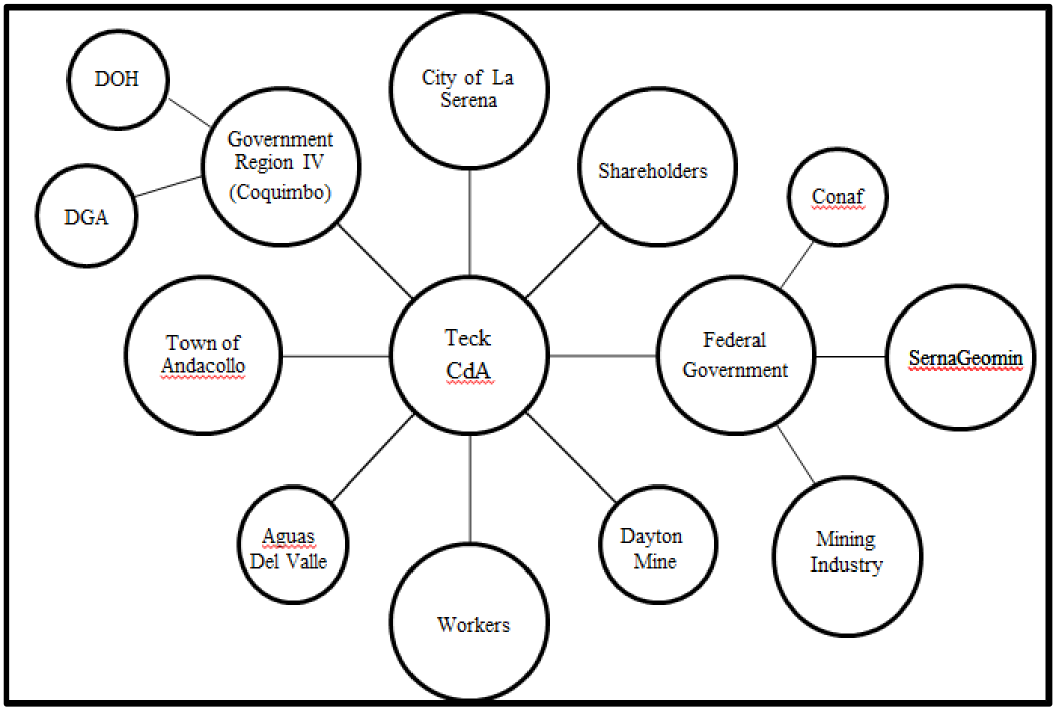
1.4 Stakeholders

Teck's Highland Valley Copper and Carmen de Andacollo mines operate close to communities (Figure 1-3). The proximity and interdependency of these communities of interest to the mines create a rather complex canvas with respect to stakeholders' relationships, which can be impacted by mining activities such as surface or groundwater extraction. Figure 1-4 illustrates a simplified overview of the primary stakeholders related to the CdA mine; bigger versus smaller circles intend to indicate relative level of influence with respect to water management. These various stakeholders have levels of interest and agendas that vastly differ between one another. The gain of one stakeholder may benefit one player while being detrimental to another. Nevertheless, each one of these is or can be impacted by the mine's activities, and each has the potential to affect the decision and/or the flexibility of the company to operate.

Given the number of stakeholders involved with mine operations, one can appreciate that "group dynamics" is typically slow, i.e. decisions and/or changes do not happen overnight. The public consultation and regulatory processes are lengthy, compared to the operational necessities of an active mine site. For these reasons, the strategic decisions related to mine water management need to be considered over the mid- to long-term, and risk & opportunities should constantly be on the company radar.

Figure 1-3: Location plan of THVC (a) and CdA (b) mines (images from Google Map© 2015).

Figure 1-4: Simplified view of stakeholders involved with CdA's water management.



2: Water Cycle in the Mining Industry vs. Teck Sustainability Strategy

This chapter describes the role of water in mining in terms of application and relative quantities used for the three mine sites under study. The systems currently in use at Teck to control water consumption are discussed. The chapter concludes with the integration of Teck's water management with the corporate sustainability strategy.

2.1 Water Cycle in Open Pit Mining

As mentioned in section 1, the THVC, CdA and QB2 operations use a flotation process to extract the copper from the ore-bearing rock and subsequently produce a concentrate that is typically ~40% pure copper. In addition to consuming large amounts of electricity, the ore processing plant is typically the primary consumer of water for these mines, as is typically the case for the vast majority of mine operations. In most large mines, the primary source of water for the plant comes from reclaim water from the tailings dam, i.e. the water recycled following the deposition of the solids phase of the tailings slurry (typically at 45-55% solids by weight). Although any reclaim system is ideally designed as a closed-loop system, there are inherent water losses mainly related to evaporation, seepage and entrainment, i.e. water fraction stored in the tailings and not practically recoverable. The relative contribution of any of the losses is highly depending on climate, location and operation conditions.

Excluding the entrained water, the average water reclaim rate ranges from about 55 to 70% (G. Beale, 2015, pers. comm.), with minimum and maximum of about 35% and 90% (for northern climates), respectively. To put this into perspective, Teck's Highland Valley Copper mine reclaims 81% of the water from the TSF (Rojas, 2012), which exemplifies "Industry Best Practice". The remaining 19% represents an annual volume of ~15Mm^3 that needs to be compensated for from another source – this missing portion is called "make-up" water. The make-up water typically comes from surface water sources (rivers, lakes, oceans) and/or groundwater sources (aquifers, pit dewatering, and pit slope depressurization).

Depending on climate and location, the make-up water can represent a significant operating cost (OPEX) to mine operations, primarily related to pumping, electrical and pipeline requirements. As such, mine operations should generally minimize make-up water requirement by using and sourcing their water efficiently.

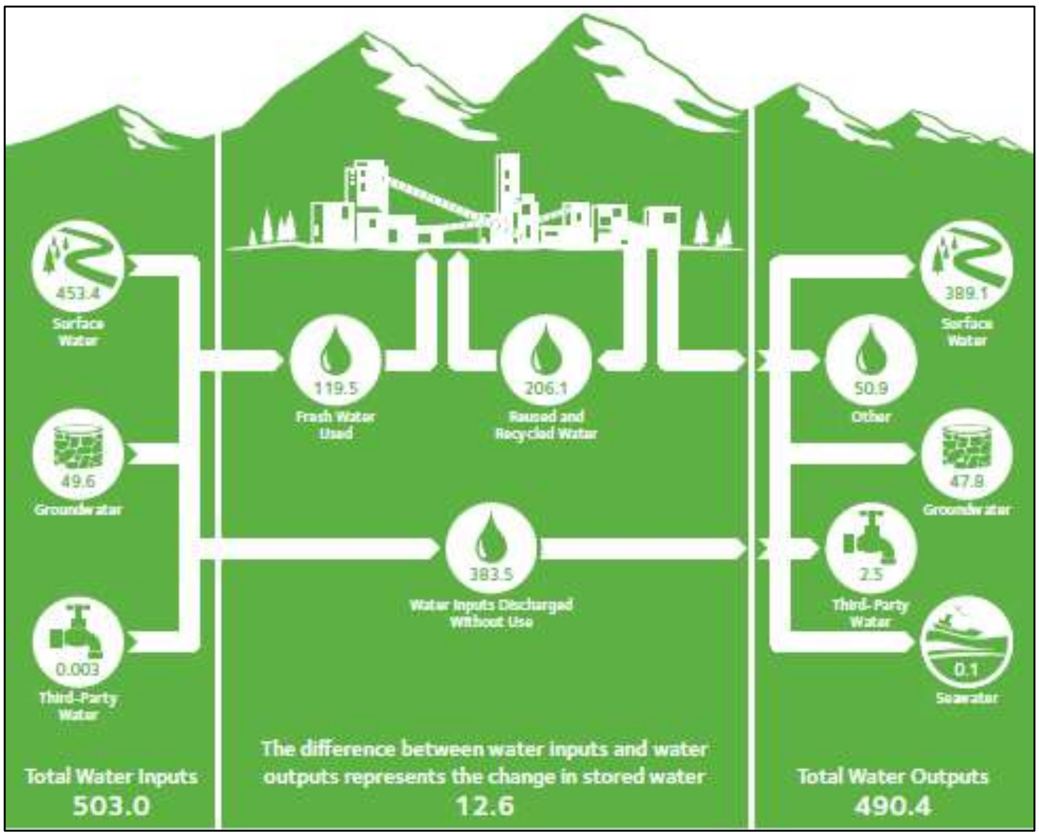
The first step towards setting water efficiency targets is to develop an understanding of the mine water balance, which accounts for the volumes of water that flow into and out of mine operations and associated watersheds. Teck developed water balances at all operations in 2013. The development of a water balance for a mine site can be a complex exercise and the accuracy acutely depends on the frequency and quality of the input data. As such, the quality of the 2013 site water balances developed by Teck likely range from accurate (e.g. THVC) to a reasonably good indication of actual conditions. The water balance development process, by itself, allows identification of specific areas of missing or weak data, so that steps can be taken and budget developed over time to narrow down the gap of uncertainties. For example, the Carmen de Andacollo (CdA) mine invested several hundreds of thousands dollars in 2013 to equip the tailings seepage collection pond and pit sumps with flow meters, and spent significant efforts at controlling water flows so they could be measured accurately.

At this point, it is important to put things in perspective, i.e. how much water does Teck use? In 2013, it is estimated that Teck used a total of 325.6 million cubic metres (m^3), of which 119.5 million m^3 was fresh water, and 206.1 million m^3 was reused or recycled water (Teck, 2013). In comparison, the 2013 water consumption for the entire Metropolitan Vancouver was in the order of 1.1 Mm^3, based on average 480L/day per capita consumption for 2013. This means that Teck roughly used over 100 times more freshwater than Greater Vancouver in 2013. Although this figure may appear high, it could be worse since Teck's mining operations recycled and reused the same water approximately five times on average before returning that water to the environment. Figure 2-1 shows the Life Cycle of water for Teck in 2013, which highlights inputs and outputs.

The consumption of water for mining purposes can be expressed in different ways, but m^3/T of mineral produced is likely the most widely used and arguably the most useful. Ore processing by flotation to produce concentrates tends to consume considerably more water than hydrometallurgy (leaching, solvent extraction and electro-winning (SXEW)), therefore it is important to differentiate the type of process with respect to water consumption. For instance, an average water consumption rate of 0.63 m^3/T is reported for concentrate production in Chile, versus 0.09 m^3/T for hydrometallurgy (Teck, 2015b). As a general rule, a flotation circuit is typically used to process sulphides-bearing ore, while hydrometallurgical processes are typically used for oxides-bearing ore.

Figure 2-2 shows the average consumption rate of fresh water per tonne of mineral produced in Chile (*Comision Chilena de Cobre*, COCHILCO, 2013), where high quality statistical data on water is collected by the government. The freshwater consumption rate for actively-producing facilities range from 0.35-0.84 m^3/T in Chile. The higher values correspond to operations where it is not possible to efficiently recycle water from the tailings storage facility (TSF). In comparison, the freshwater consumption rate from hydrometallurgical facilities range from 0.06-0.15m^3/T. COCHILCO (2013) reports that the rate of water recycling from mine ore processing facilities was 73%. The water recycling rate at CdA was estimated at 76% for 2014, i.e. slightly above average. It is interesting to remark that fresh water extraction rates have remained essentially constant in Chile for the period of 2009-2013.

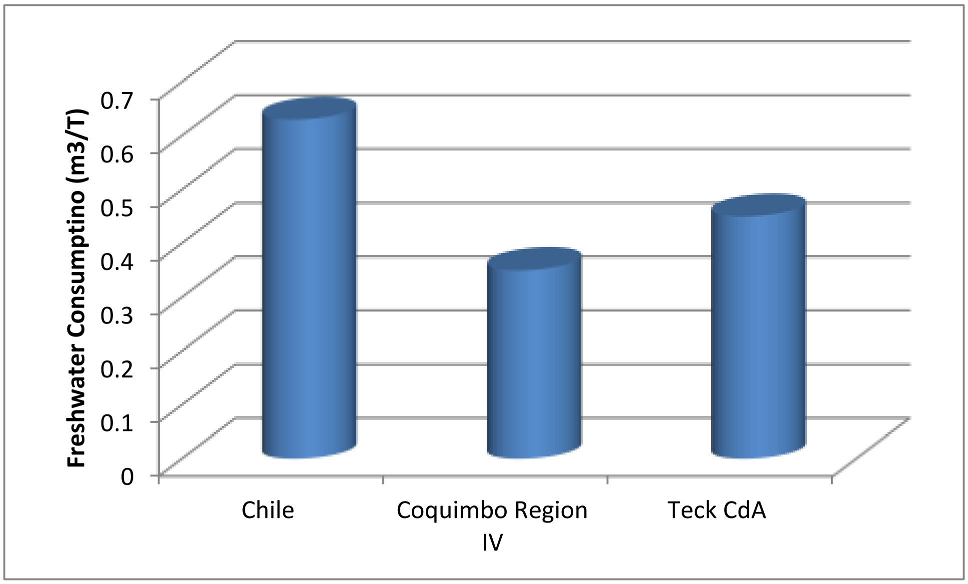
Figure 2-1: Teck’s 2013 Company-wide water balance.



(Adapted from Teck, 2013).

On the other hand, the consumption of sea water for ore processing has steadily increased from 0.32m^3/s to 1.29 m^3/s (COCHELCO, 2013) for the same time period. This general increase is presumably what allowed Chilean operations to maintain fresh water extraction rates nearly constant over the past five years, despite a general increase in copper production. This data suggests that expansion projects and/or new mines are shifting towards sea water as a primary process water source. Of all the sea water pumped to ore processing facilities, approximately 45% is desalinated and 55% used raw (salted). As will be discussed in chapter 4, the use of sea water for ore processing represents a significant cost for mine operations either related to the CAPEX and OPEX of the desalination plant, or the maintenance issues associated with corrosion.

Figure 2-2**:** Average consumption rates of freshwater (m^3/T) for Chilean mining industry.



(Source: COCHILCO, 2013; Teck, 2013)

2.2 Teck's Integrated Water Management Plan

Following the development of mine site water balances in 2013, each Teck operation completed integrated water management plans (IWMPs) that describe how water will be managed in order to:

- Contribute to meeting corporate sustainability goals;
- Provide direction and strategy to address water management risks and challenges;
- Establish how water management infrastructure performance will be monitored and reviewed;
- Determine staffing resources that are required for water management;

Each plan also aims to provide context on how an operation fits into the area watershed and its corresponding regulatory context. The intent is that IWMPs will be updated annually in conjunction with each operation's water balance. The IWMPs for both CdA and HVC (Teck 2015a, 2015b, respectively) were reviewed as part of this project. The documents were found to vary significantly in terms of content, focus and level of details. These differences suggest a degree of "personalization" of the plan, and also the existence and quality of water data since the IWMP initiative is still in its infancy stage.

Water is an increasingly scarce resource and, as a result, Teck is working at optimizing water use. The water balance consists of data on the volume of water inputs, use, reuse, recycling and outputs at each operation. It is complex due to the variability of natural factors such as rainfall, snowmelt and the diversity of the climate where Teck operations are located. These factors can all affect the flows within aquifers and surface water. Understanding the water balance is the key to improving water management practices and to enabling better decision-making.

As previously stated, water supply can create a business risk for mine operations. Teck is developing and utilizing alternative water sources such as seawater and municipal wastewater, and engages with communities of interest to collaborate with them on fair water allocation. The IWMPs allow to clearly define the roles and responsibilities of Teck's personnel with regard to water conservation, efficiency, and management for site projects. The IWMPs also provide professionals with a roadmap to guide their activities in alignment with laws and regulations (e.g. Table 1-1).

One of the challenges that BC mines such as HVC will face in the future is the amendment to the Water Sustainability Act that the BC government is currently finalizing. It will replace the old BC Water Act, which only vaguely provides regulations for surface water use. HVC has historically operated with little regulation on water use due to the largeness and relative lack of clarity of the Act. In comparison, the new act proposes to license groundwater. Table 2-1 summarizes the key changes between the old versus new Water acts in British Columbia.

The current Water Act will remain in force until the Water Sustainability Act is brought into effect in 2016. At that time, the Water Act will be repealed. Under the new Act, government will manage surface and groundwater as one resource. The new Water Sustainability Act proposes to determine the rights of a water license (both surface and groundwater) based on available quantity in order to avoid over-allocation of the resource. The primary difficulty with this allocation method lies in the difficulty to measure groundwater quantities, i.e. not from an extraction point of view but from a reservoir capacity – i.e. how much water is contained in the aquifer a mine is pumping from? This capacity volume can be a dynamic value depending on recharge rates, etc. One potential alternative may be for a company to purchase the water rights to the entire aquifer, as opposed to a fractional volume of its capacity. In a sense, this scenario would be similar to the questionable old practice of draining entire lakes, and replacing them with artificial "compensation lakes".

The new Act also seems to lack of clarity as to what is "passive" versus "active" water consumption. From a mining company's perspective, groundwater consumption in the pit is considered passive as it is inherent to open pit mining. On the other hand, it can also be considered active since the groundwater extracted from the open pit is typically used at the process plant. For instance, if the mining company had to extract to groundwater from the open pit but did not want to use the groundwater, then it should be discharging it back to the watershed. The discharge could in turn bring up conflicting legislation, which is not discussed in this paper.

In light of changing regulations relative to the control of water in both British Columbia and Chile, Teck has a strong interest in reducing fresh water consumption for current and future projects. Reducing freshwater usage may be cheaper in some cases, while in other cases it might be more advantageous for a company to obtain more expensive make-up water in order to avoid using local freshwater. However, beyond the potential financial benefits of reducing freshwater consumption, it is a corporate responsibility and is compatible with Teck's sustainability strategy as discussed below.

Table 2-1: Summary of changes to regulations on water usage in British Columbia.

Old BC Water Act	**New Water Sustainability Act**
▪ Only the wells were permitted ▪ Actual volume of groundwater ▪ Only charged a fee for surface water use	▪ Will include a fee for groundwater consumption ▪ Process for licensing is proportional to total volume available

(Source: BCME, 2014)

2.3 Teck's Sustainability Strategy

Teck Resources Ltd. has prepared an annual sustainability report since 2000. In 2009, the company developed a formal sustainability strategy, which defines the corporate approach to responsible resource development. The sustainability plan outlines six areas that represent the biggest challenges and opportunities for sustainability-related work: community, people, water, biodiversity, energy, and materials stewardship. Teck's nominations as Corporate Knight within the top 100 most sustainable large companies in the world for five consecutive years illustrate the company's commitment to sustainability. The present paper discusses the implication of water for three Teck mines, which primarily involves three of Teck's six sustainability component: communities, energy and water.

Teck intends to be a leader in water stewardship (Teck, 2013). The company's philosophy on water management is based on (i) maintaining water quality, (ii) using water efficiently, and (iii) collaborating with communities of interest (COIs) to ensure the fair allocation of water. As a benchmark, Teck milled and processed (by flotation) approximately 67Mt of mineral in 2013 which required on average 0.35m^3 of water per tonne of ore processed (Teck, 2013).

Energy costs are one of Teck's most significant operational expenditures. The corporate approach to energy management is integrated within cost reduction and business improvement programs, with the objective to identify and implement initiatives that improve energy efficiency while also lowering costs and improving business processes. Diesel use primarily for operating haul trucks represents about 38% of total energy used yearly (Teck, 2013). For this reason, the company embarked on a mission a few years ago to improve haul truck productivity in order to reduce both operating costs and green-house gas (GHG) emission. As discussed in section 3.2 ore and waste materials can contain up to 10% water by weight, which is relevant from a fossil fuel efficiency perspective.

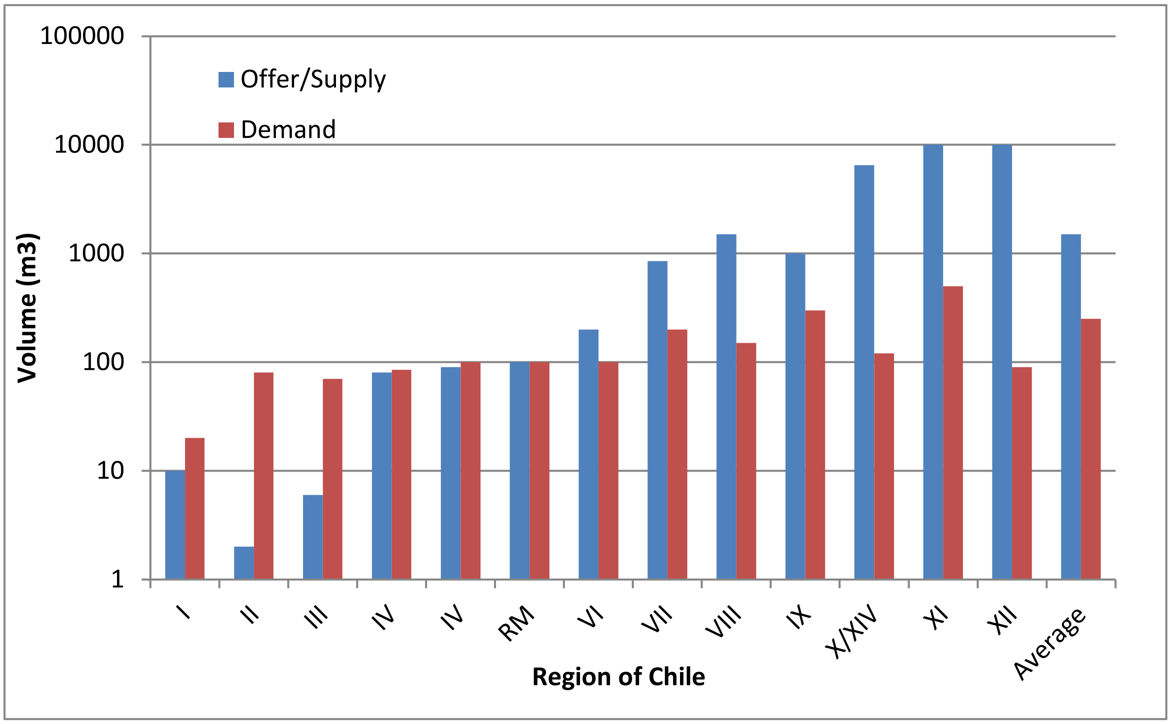
In addition to possibly reducing the cost impacts associated with "wet mining", the reduction of water content in the mine through dewatering appears as an attractive solution to improve trucks pay load. The extraction of groundwater from open pit mines could also lead to potential reduction in fresh-water make up requirement. It is the intent of this paper to identify potential initiatives such as these, which align operational needs with Teck's sustainability strategy.

Generally speaking the supply of freshwater as primary mine process make-up component is easier and cheaper in British Columbia than in Chile simply due to climatic and physiographic conditions. For these reason, the decision for Teck to reduce freshwater usage in Canada is likely driven more by financial interests and sustainability objectives than by sheer necessity. For Teck operations in Chile however, this decision is rather based primarily on legal requirements (e.g. water permit restriction) and water availability than by costs.

Figure 2-3 illustrates this difference by showing the relative volumes of water available (*oferta*) and water needs (*demanda*) for Chile in 2013 (DGA, 2013). The mining industry in Chile is the second water consumer after agriculture. In parallel to general increase in copper production over the past five years, the demand for water has also increased steadily over the same period. From Figure 2.3 one can observe that the water demand exceeds availability for regions I to IV, which correspond to the mineral-rich, arid to desert areas of North-Central to Northern Chile.

Freshwater use by mining operations is currently planned to nearly double from 2007 levels by 2030 (DGA, 2007) for Chile regions I-IV. For these mining regions, water consumption rates are currently regulated at 30.7 m^3/s, of which 42% is dedicated to surface water and 58% to groundwater extraction. Of this amount, 17% is allocated to Region IV where CDA is located. Although likely inaccurate and subject to changes, these prediction suggest that competition for the water resource will intensify in the future. With life-of-mine (LOM) plans beyond 2035, it is thus important for Teck to be ready to face the realities of the water challenges in Chile.

Figure 2-3**:** Water supply versus demand per region in Chile.



(Source: DGA, 2013).

3: Impacts of Water at Teck's Copper Open Pit Mines

This chapter briefly describes the mines under study and presents a high-level overview of the water balance developed by Teck for each of the three sites, principally in terms of access to water. It follows with presenting the effects of groundwater on mine operation activities at HVC where groundwater is encountered in the pits in substantial quantities. The financial costs of process and make-up water supply are then discussed to illustrate the significance of water on a mine operation's budget.

3.1 Water Balances

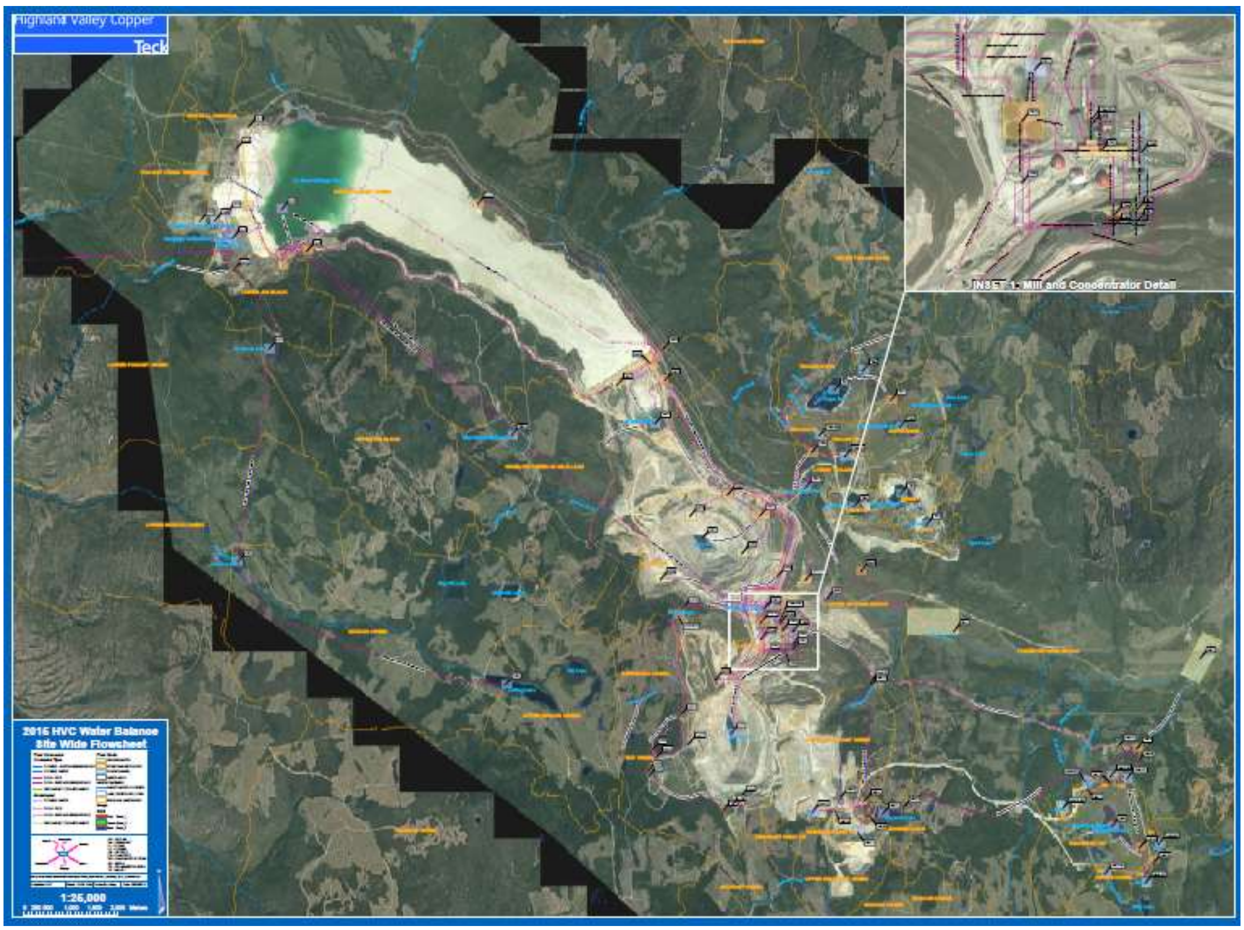
Like for any modelling exercise, the accuracy of a water balance model depends on the accuracy of its input parameters and assumptions. The accuracy of the HVC and CdA's water balance models will improve, as the models are reconciled on a yearly basis against measured values. For most mine sites, the water balance focuses on the tailings storage facility (TSF) since it typically represents the principal water reservoir and connects directly to the ore processing facility, i.e. the principal water user. The water balance for a mine site is usually developed empirically via a spreadsheet or statistically using GoldSim© or similar software.

THVC practices active open pit dewatering and a consorted effort has been expanded since 2010 at instrumenting water collection facilities with flowmeters. As a result, the site water balance is relatively accurate. In comparison, the CdA water balance implies several assumptions due to the current lack of flowmeters coverage. It is considered a representative water balance as the primary inputs-outputs are measured accurately. CdA is currently improving its water-monitoring network with the installation of additional flowmeters in 2015. The water balance for each site is briefly described below in a simplified way.

THVC

THVC is located along the Highland Valley (El. 1,200m) near Logan Lake, BC and receives approximately 380 mm of precipitation per year, compared to evaporation rate of 570 mm/year. The TSF is also located at the bottom of this valley and receives discharge from various tributaries, which more than compensate for the evaporation loss of the impoundment. The Valley pit is the largest pit on site, and is subject to active mine dewatering to allow mine operations to proceed. The process facility obtains 81% (~58Mm^3 in 2010) of its water from the TSF reclaim system. On any given year, the make-up water is provided by a combination of pit dewatering and/or water from the North Thompson River (~13Mm^3 in 2010). The water intake at the river is located approximately 30km away from the process plant, and 500m vertical below at the Spatsum pump station. The make-up water requirement translates to ~0.28 m^3/T of copper produced, which is a fairly low value in the industry. Figures 3-1 presents the visual version of the water balances developed for HVC (AMEC, 2013).

Figure 3-1:**:** 2013 water balance for Highland Valley Copper mine.

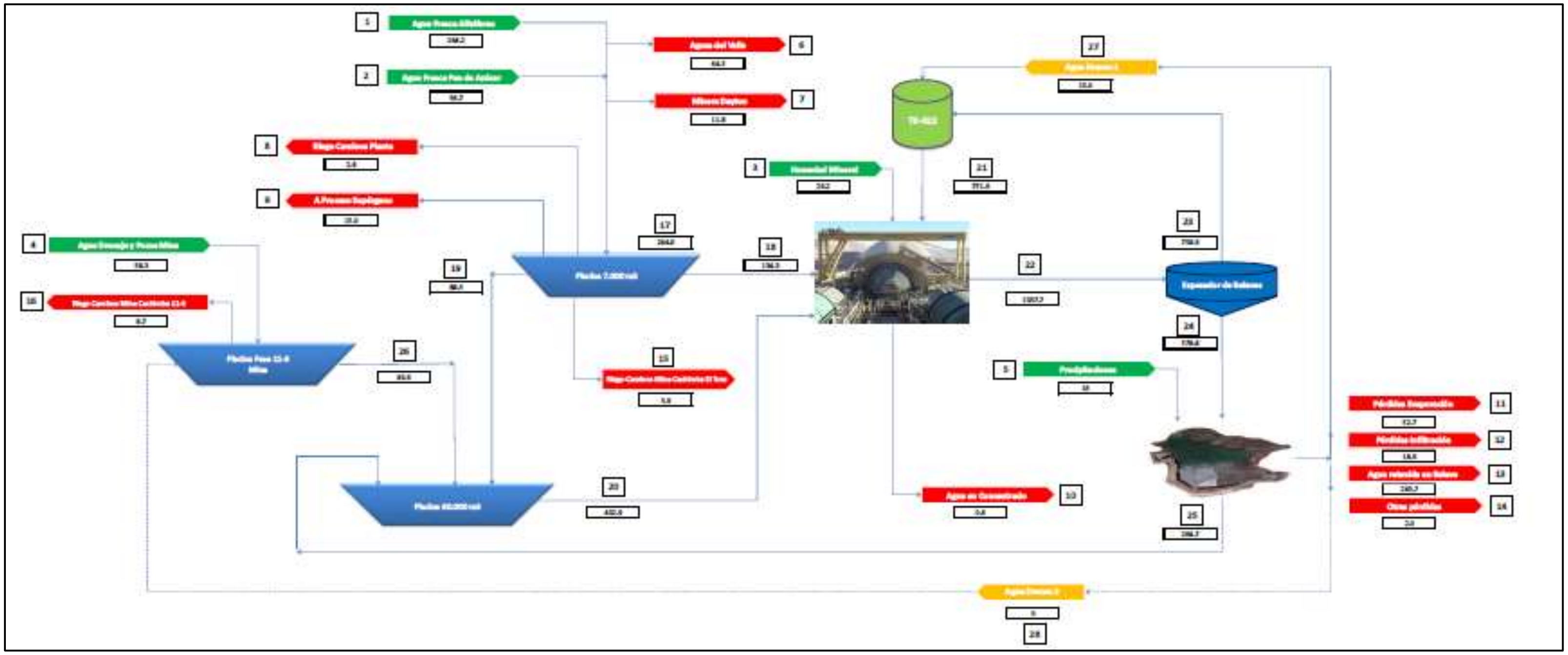


(Source: Teck, 2015b).

CdA

The Carmen de Andacollo mine site is located on a high mountainous plateau (El. 1,085m) approximately 75km from the city of La Serena in the Coquimbo region of Chile (region IV). The mine site receives an average of 125.7 mm/year of precipitation and records an average evaporation rate of 2,300 mm/year. In 2013, the ore processing facility used over 40Mm^3 of water, of which ~8Mm^3 came from the TSF reclaim system. This means that over 25% of the make-up water required for the process plant needs to be sourced externally. This make-up water requirement translates to ~0.50 m^3/T of copper produced. In the case of CdA, freshwater is located about 40km away from the mine, and about 1,000m lower in elevation. In order to avoid interference with farmers' groundwater supply, these wells were drilled very deep and hence operate at a much higher cost. Figures 3-2 presents the visual version of the water balances developed CdA in 2013.

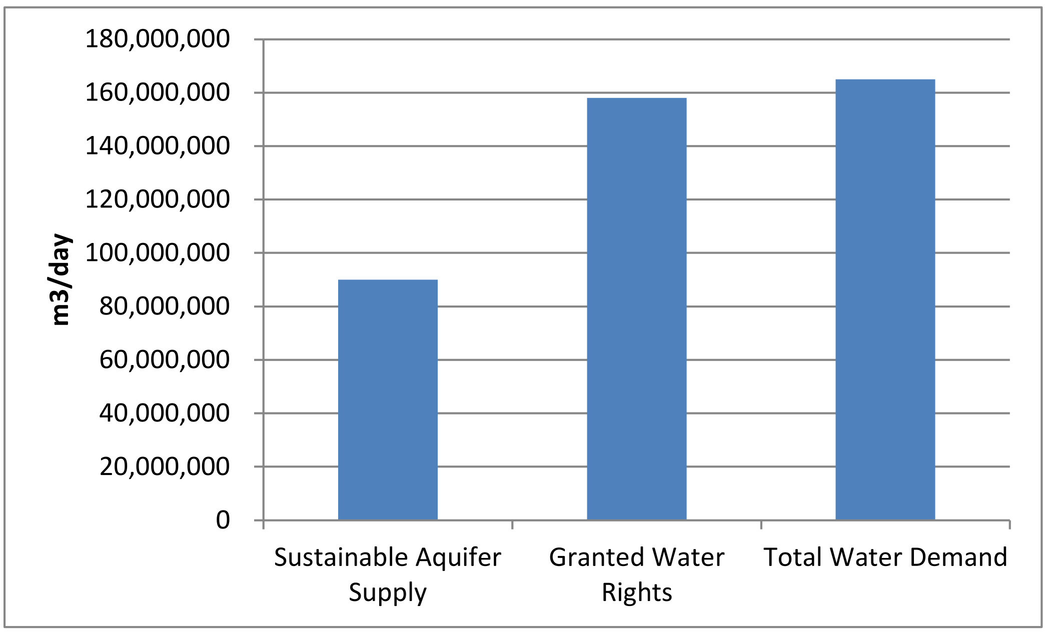
Figure 3-2**:** 2014 water balance for Carmen de Andacollo mine.



(Source: Teck, 2015a).

Figure 3-3 shows the water supply versus demand for groundwater of the Elqui River, which is the primary make-up water source for CdA (DGA, 2013). The figure shows the water rights for groundwater from aquifers of the Elqui River valley, for which the maximum sustainable extraction rates were determined. From this plot, one concludes that the water demand on permits already granted and permit applications greatly exceeds sustainable levels from the aquifers. For this reason, according to article 65 of the *Codigo de Aguas*, the DGA is contemplating to declare restriction of new groundwater extractions in all sectors of the Elqui valley. This situation creates a risk of groundwater acceptability for CdA in the future.

Figure 3-3**:** Groundwater supply and demand from Elqui Valley aquifers.



(Source of data: DGA, 2013)

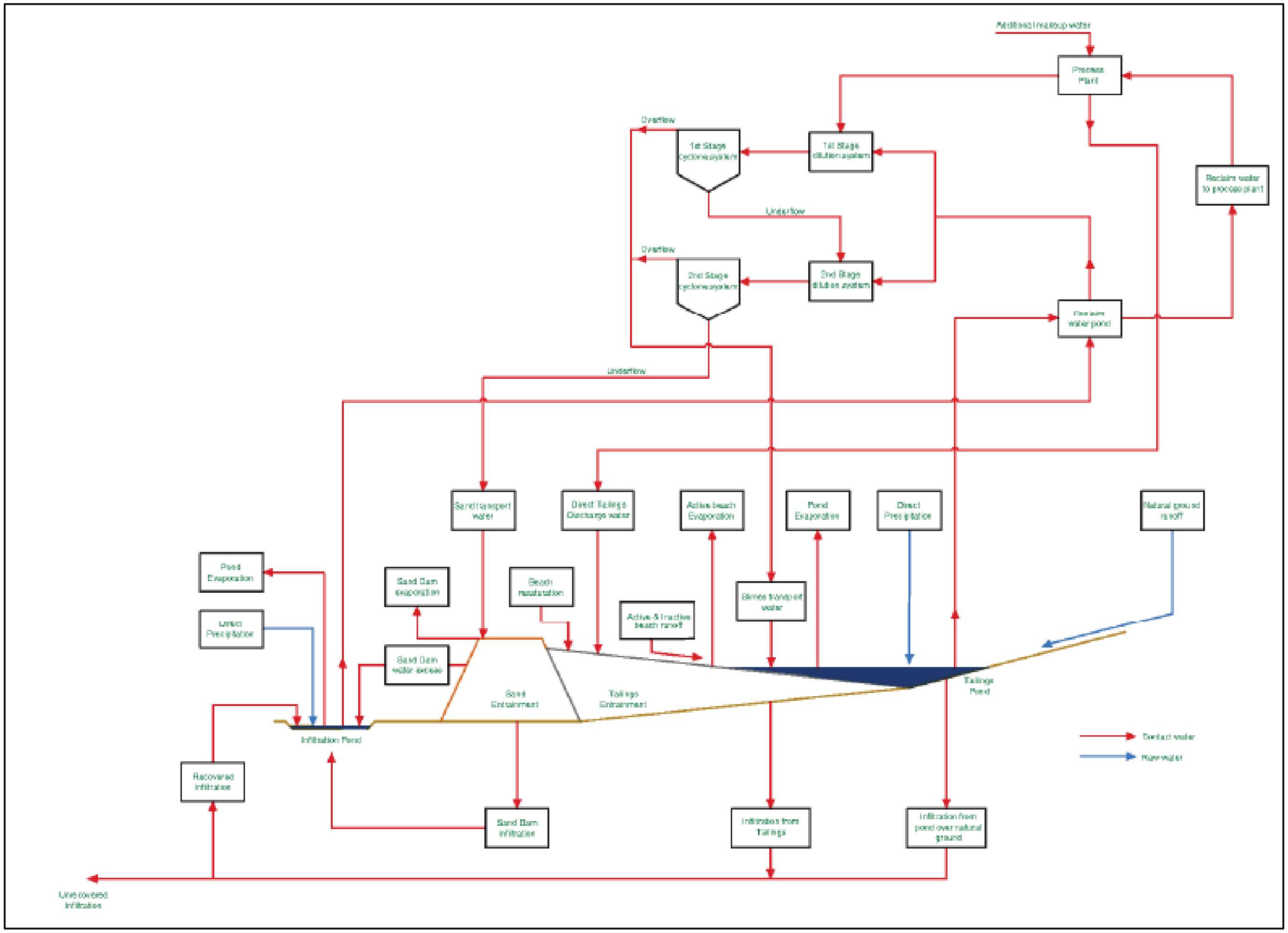
<u>QB2</u>

The QB2 hypogene project is an expansion of the existing Quebrada Blanca mine, which currently processes oxide copper ore via a solvent extraction and electro-winning (SX-EW) plant. The mine site is located in the Atacama Desert (El. 4,400m) approximately 175km SW of the city of Iquique in the Tarapaca region of northern Chile (region I). The mine site receives an average of 15.0mm/year of precipitation, mainly during the months of December-January, which correspond with the Bolivian winter

(*Antiplanico*). The site is subject to an average evaporation rate of 1,730 mm/year. The QB2 project will exploit the hypogene portion of the deposit (sulphide mineralization) using a traditional flotation circuit. For this reason, although the current oxide leaching operation does not consume much process water, the QB2 project will require water volumes comparable to THVC to operate the process facility (over 43 Mm^3/year).

There is no surface water or groundwater available in substantial volumes anywhere close to the project site. The QB2 project illustrates an extreme example of complicated water supply, where the reclaim water (Choja Sur TSF) and the desalinated sea water respectively come from 40km and 170km away, and 2,000m and 4,400m lower in elevation. Due to high evaporative losses at the Choja Sur TSF, it is predicted that the operation will require approximately 70% of its water from make-up sources, i.e. desalinated sea water (over 30 Mm^3/year). Figures 3-4 presents the visual version of the water balances developed for the QB2 project (Golder, 2012).

Figure 3-4**:** Simplified water balance for the QB2 project.



(Source: Golder, 2012).

3.2 Operational Impacts

As previously illustrated by Figure 1-1 the presence of groundwater in a typical open pit mining environment can create operational issues. The following is a summary of operational impacts related to the presence of groundwater for THVC.

Drilling & Blasting

Table A.1 presents a summary of % re-drills completed over the past 5 years at HVC. Figure 3-5 illustrates an example of wet blast holes encountered in the Lornex pit on the El. 1455m level. Often if caved holes are not grouped, they are not re-drilled, which can locally impacts shovel productivity and ultimately the mill throughput (TP) due to the coarse material, but this is difficult to quantify. The annual HVC budget assumption of 1.5% for re-drills is considered appropriate since dryer conditions can be expected higher up in the pits, and can be expected to become increasingly wetter as the pit deepens. Attributing 50% of the re-drill holes to water, Table A.2 presents the summary of cost implications for re-drilling and re-loading on average about 225 holes per year at HVC. This represents over $170,000 in additional costs excluding the downstream effects mentioned here-above, which are likely even greater.

Figure 3-5**:** Overview of Lornex pit showing wet blast holes (cyan) versus dry holes (red).

Haulage

Truck productivity is generally measured in Tonne Per Operating Hour (TPOH). This KPI is dependent upon the length, grade and conditions of the haul. The impact of water on truck productivity at HVC is estimated to be ~15% reduction; this estimate appears to be consistent with the experience at Colahuasi, Chile (G. Beale, 2013). HVC assumes 2% of water by weight in the muck, meaning that each CAT 793 truck (capacity of 240T) transports nearly 5T of water. A modest 10% lowering in saturation level in the muck could reduce the hauling cost by $0.05/T. Table A.3 presents the HVC mine operations budget for 2013. Using these values, table A.4 present the estimated inefficient costs related to typical 4 weeks/year of "wet" mining conditions encountered at THVC. Wet conditions are a double hitter: you need more operating truck hours to achieve the same productions, and those trucks need more fuel/hour due to increased rolling resistance of tires and resulting increased engine load factor.

From a fuel consumption perspective, Table A.5 suggests that over 1ML/year of additional diesel is consumed to compensate for wet haulage conditions, which produces an estimated 2,812 T/year of additional CO_2 emission. The 2013 value for Carbon Tax in Canada averaged approximately $50/T CO_2. Based on this estimate, the "value" of additional CO_2 released per year at THVC as a consequence of wet haulage conditions is worth over $140,000/year in carbon credits/tax. In any case, the cost inefficiencies listed above seem comparable to a previous study carried out at Collahuasi (Appendix B).

Tire costs

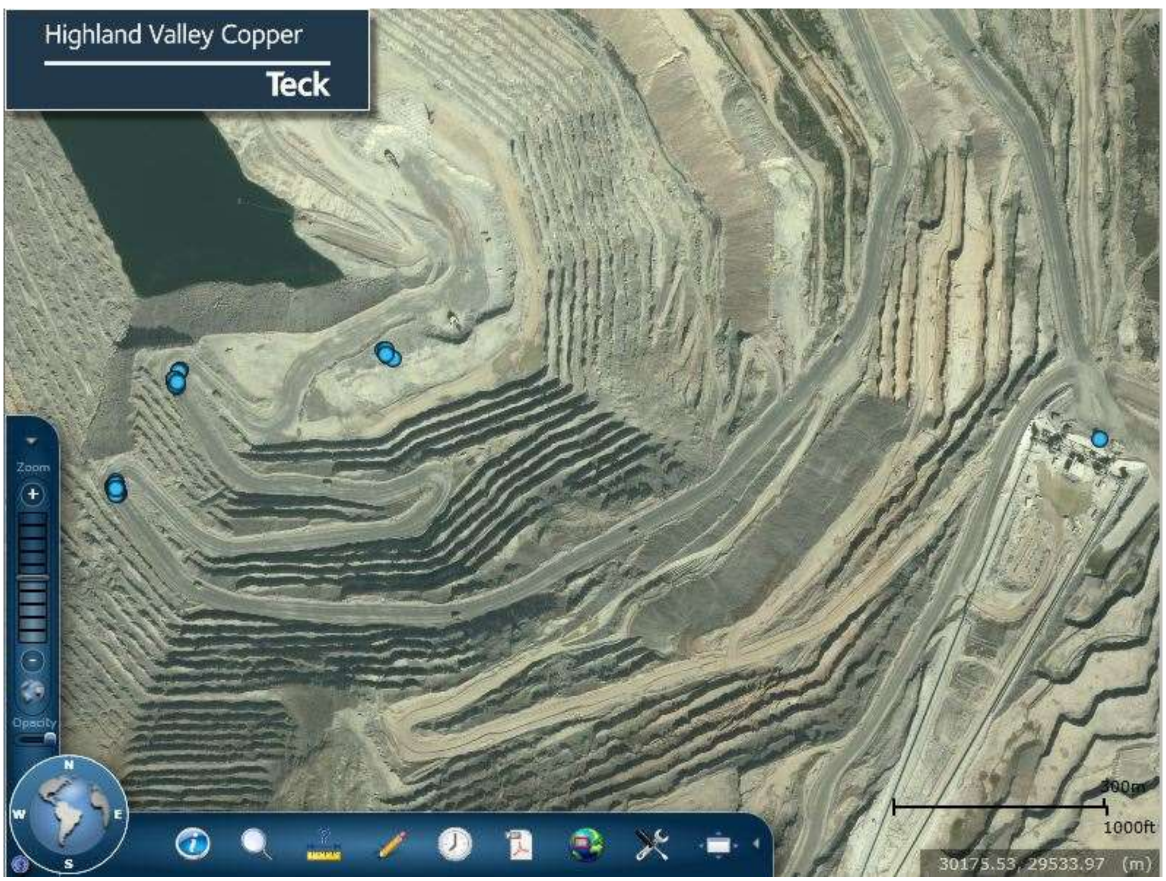
The presence of water on operating benches creates mud and traction issues and leads to increase tire wear, which is hard to quantify. The average tire life at THVC is around 7,500 hours. Assuming a 10% increase in cuts and damage to tires over 10% of the truck running distance, the cost of water-related damage on tires is estimated at ~$35k per year per truck. Accounting for a fleet of over 50 trucks at THVC, this value could amount to over $1.8M per year.

Equipment maintenance and damage

Other indirect maintenance costs are also attributed to wet mining, but appear difficult to quantify (Appendix C). The operating hours for graders required to maintain haul road operational during wet weather increase dramatically. Similar to tire wear, the presence of water causes running wear to mining equipment, e.g. damage to the undercarriage of haul trucks. The additional weight of mud build up also leads to higher maintenance costs. In extreme wet cases, the presence of mud can lead to cracking of the truck frames due to increase in strut pressures at key stress points in the mine, i.e zones of water accumulation. Figure 3-6 shows a map of excessive strut pressures recorded at THVC for the month of March 2015, which correspond to known wet areas in the Valley pit during early freshet. Other additional costs incurred by wet mining conditions include premature failure of shovel trailing cables (both sheath and connectors) and increase in light vehicle maintenance, particularly brakes and wiring issues.

Due to the difficulties in accurately estimate the annual expenses related to wet mining conditions at THVC, this study assumes a flat increase of $2M/year, which represents a 10% nominal increase to overall annual mine maintenance costs. Since wet conditions are typically encountered for approximately one month in the spring and one month in the fall, this estimate is considered somewhat on the optimistic side, although "ball park" accounting for a heavy equipment fleet of 7 shovels, 6 drills, 6 dozers and 50 trucks at THVC.

Figure 3-6**:** "SmartRoad" image of high strut pressure measurements recorded for March 2015.



(Source: HVC)

Pumping

The cost and energy effort of extracting groundwater out of the pit is also significant at HVC. The best way to decrease saturation levels in the pit wall would be with perimeter pumping high on the slope and behind the wall. Figure A.6 illustrates the effect of dewatering on the piezometric surface. The pumping of 1m^3/hour over a height of 1m uses approximately 4.5W @ 6,000usgpm (rough average flow for the Valley pit). Assuming a nominal reduction of 100m of hydraulic head, HVC could save 619 kW. At 90% availability and operating 364 days per year HVC could save $243K/years @ 0.05 $/kWh in electricity costs alone. Other indirect benefits would include reduced quantities of pipeline required to lift water from lower elevations, fewer temporary sumps, etc.

Table 3-1 summarizes the estimated annual cost associated to “wet” mining at HVC, which total over $8M/year in increased mining cost or approximately 11% of annual operational costs from the mine operations budget for 2013. The total value is considered a preliminary estimate as a number of assumptions and approximations require validation. Nevertheless, it likely represents a representative estimate of the financial implications of “wet mining” at HVC.

Table 3-1**:** Summary of estimated annual “wet-mining” costs for HVC.

Water implication	**Cost (CAD)**
Truck productivity	$3,370,752
Re-drill	$170,000
Extra fuel for trucks	$900,000
Pumping	$243,000
Tires	$1,601,600
Equipment wear [1]	$2,000,000
Estimated TOTAL	**$8,285,352**

Note: [1] Preliminary estimate; would need validation.

(Source: S. Fortin, 2013)

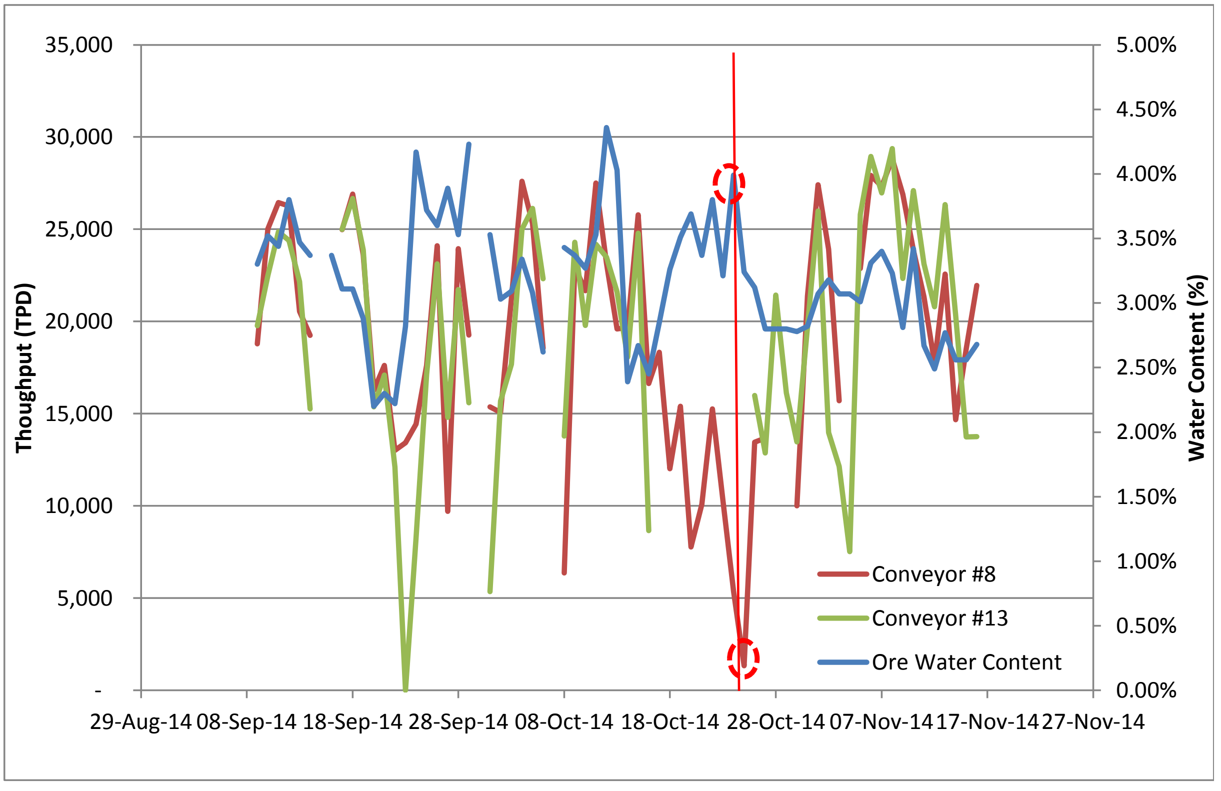
In comparison to HVC, groundwater is also encountered in the CdA pit but does neither cause geotechnical stability nor operational issues mainly because it is typically localized within areas of the pit and that solar radiation and evaporation take care of drying out haul roads. For these reasons, the presence and encounter at CdA is primarily considered an opportunity for make-up water supply.

Similarly, the QB2 open pit is predicted to encounter limited amouts of groundwater (~2,500 m^3/day groundwater inflow, Artois (2012)) due to the low degree of fracturing of the rock forming the hypogene deposit. This represents only ~3% of make-up water requirements. For the same reason, the issue of groundwater in the QB2 pit is associated with the generation of relatively high pore pressures which could affect the geotechnical stability of pit walls. Depressurization measures such as horizontal drains combined with a few pumping wells are planned to ensure pit wall stability.

Mill Productivity

The ore rock sent from the mine to the mill typically goes through a mechanical comminution process starting with the primary crusher. This process aims at maximizing ore throughput, which is a measure of productivity of the processing plant. As shown on Figure 3-7, the moisture content of the ore can have direct impact on throughput. According to the experience of Quebrada Blanca mine between August 2014 to January 2015, ore moisture content above 2% could reduce throughput by up to 100% (i.e. temporary shut-down of the crusher) due to the temporary clogging of screen decks. Therefore, there is a clear interest for the mine to monitor and control the ore moisture to prevent mill operational impacts.

Figure 3-7**:** Relationship between ore moisture and throughput at the QB mine.



(Source: Teck Quebrada Blanca, 2014)

3.3 Process Water - Financial Implications

This section discusses the relative costs of different sources of process water for HVC, CdA and QB2. The analysis is based on a detailed review of the site water balance and records of pumping volumes and electricity consumptions. Due to the existence and availability of data for the various sites, it was not possible to select a common year for all three sites to serve as a basis for comparison. Nevertheless, annual copper production did not vary greatly across the review period so the analysis is considered valid, although not accurately comparing “apples” with apples”. The review used the following data sets:

i. HVC – Year 2010 data was used for water balance and copper production, due to the access to reliable summary of energy records for that year (Rojas, 2012).
ii. CdA – The water balance, energy consumption and copper production for 2013 were used.
iii. QB2 – All values used (water balance, energy consumption and copper productions) refer to the predictions per Teck’s 2012 Feasibility Study for the project.

Table 3-2 summarizes various key cost and performance indicators following the review of annual water and electrical consumptions for THVC, CdA and the QB2 project. Appendix D includes selected data used in the preparation of Table 3.2. The water volumes used to develop this table refer to total water volume and total make-up volumes, i.e. it does not consider the recycling of water at the mine site, thus providing a “raw” image of water consumption. This table clearly demonstrates the advantages to (i) minimizing fresh-water requirement for make-up water, and (ii) maximizing reclaim volumes from the TSF. Results from Table 3.2 allow the following conclusions:

- Teck’s operations in Chile carry a higher cost of water due to combination of high electrical cost and lower reclaim rate (evaporation), i.e. higher contribution of make-up;
- Unit cost of make-up ranges from 2-5 times the cost of reclaim or wells, therefore strong incentive to generally reduce make up water;
- CdA uses 75% as much water as HVC, for an annual copper output just under 40% of HVC’s production;
- Evaporation rates are very high for both CdA and QB2 (over 100 times more than annual precipitations);
- Compared to HVC, reclaim rates at CdA are at least 7% lower and QB2 very low;
- The two factors above result in higher demand for make-up water, which is 2-4 times more expensive for CdA and QB2 than HVC’s unit rate;
- THVC uses the most water per ton Cu produced (1.46 m^3/T versus 0.89 and 0.94) for QB2 and CdA, respectively. However, it uses the least make-up water (best recycling rate).

- The cost of water per tonne Cu produced is about 5% of total operating cost/tonne for HVC and CdA, compared to 12% for QB2; it is a considerable cost.

Table 3-3 shows a comparative summary of unit cost for water from different sources at THVC. The THVC example shows that the unit cost of water produced by dewatering activities tends to be ½ the cost of make-up water (i.e. from Spatsum), although considerably more expensive than reclaim water. In comparison, make-up water tends to be 3-5 times more expensive than reclaim water. Interestingly, these relative differences in unit costs per source seem to be relatively similar to those calculated for CdA and QB2.

Table 3-2: Summary of key performance and cost indicators of process water consumption and usage.

Key paramaters	Units	THVC[1]	QB2[2]	CdA[3]
Precipitation	mm/yr	382.5	15.0	125.7
Evaporation	mm/yr	570	1,730	2,300
Average Daily Copper Production	tpd	135,000	135,000	55,000
Average Annual Copper Production	tpa	49,275,000	49,275,000	20,075,000
Annual Electricity Consumption (for water)	kWh	647,933,273	407,883,000	110,130,078
Annual Water Consumption	m^3	71,899,117	43,800,000	43,167,640
Reclaim water	%	81	40	74
Unit rate of electricity[4]	$/kWh	0.031	0.115	0.121
Annual Energy Cost - electricity (for water)	$/yr	20,137,766	79,836,545	13,325,739
Average Unit water Cost per year	$/m^3$	0.28	1.82	0.59
Unit water cost - Pit wells	$/m^3$	0.27	N/A	N/A
Unit water cost - Reclaim	$/m^3$	0.11	0.58	0.23
Unit water cost - Make-up	$/m^3$	0.57	2.36	1.44
Water per tonne Cu produced	m^3/t	1.46	0.89	2.15
Make-up Water Unit Consumption	m^3/t	0.28	0.62	0.52
Average Cost Water per tonne produced	$/t	0.41	1.62	1.26
Reclaim Water per tonne produced	m^3/t	1.18	0.27	0.42
Mining Production Cost	$/t Cu	2.21	2.45	1.98
Milling Production Cost	$/t Cu	5.29	10.58	9.62
Total Production Cost[5]	$/t Cu	7.50	13.03	11.60
Water Cost as % Total Cost	%	5%	12%	11%

Sources & Notes:

1. Year 2010 water and energy consumption data for THVC. December 2014 Actual Year-to-date costs values, Teck HVC.
2. Water and energy cost estimation derived from data in Teck's 2012 Feasibility Report.
Production costs from June 2014 Optimization Parameters, Teck Chile. (0.85USD:1.0CAD)
3. Data from J.C. Gomez, Spdt. Water Management at CdA.
Production Costs December 2014 Actual Year-to-date values, Teck Chile.
4. All costs expressed in CAD.
5. Excluding General & Administration (G&A) Costs.

Table 3-3**:** Comparative summary of unit cost for various sources of make-up water at HVC

Source	**Price**	**Unit**
Potable water wells	0.08	$/m^3$
Reclaimed water	0.11	$/m^3$
Spatsum (make-up)	0.57	$/m^3$
Dewatering and deep wells	0.27	$/m^3$

(Adapted from Rojas, 2012)

In addition to improving performance and reducing operating costs in the mine, the use of pit dewatering systems to provide make-up water to the ore processing facility can provide significant cost and energy savings. In a simplified way, the cost and energy savings incured from a reduction in make-up water requirement could be spent towards open pit dewatering; this assumes excluding potential geotechnical or slope design benefits from increased dewatering, which can also be substantial. While this could be seen as a zero-sum transaction, it does offer sustainability benefits and could justify investing further resource into pit dewatering activities.

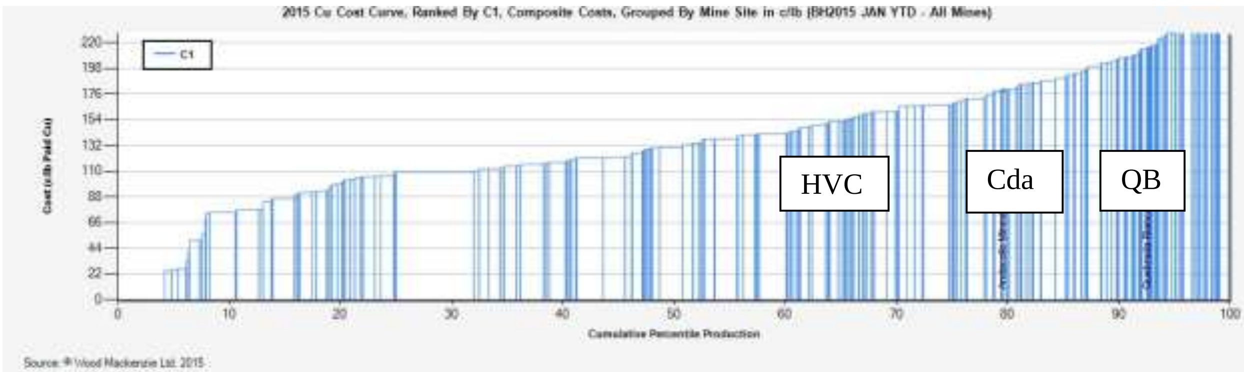
As suggested per Table 3-1, the cost of obtaining process water can represent a significant portion of the overall operating cost of a mining operation. In an industry known for generally high Capex, long payback period and relatively low profit margin, it is clearly advantageous to minimize operating costs in order to position strategically on the C1 cost curve. Improving water management to produce cheaper water can clearly contribute to this strategy, with the enhanced benefit of sustainability. On the other hand, implementing open pit dewatering infrastructure requires significant up-front capital investments.

The easiest way to minimize water cost is logically to obtain it from local sources, which as offers two principal options for most mines: (i) reclaim water from the TSF, and (ii) groundwater from pit dewatering activities. As discussed earlier, the TSF pond should be operated carefully so as to minimize evaporation and other losses. The following discussion focusses on the advantages of obtaining process water from open pit dewatering. Firstly, the long-term financial benefits of massive pit dewatering have been reported by various mining companies (Beale, 2011). According to this renowned practitioner, “slope depressurization has a 5:1 return – for every $1 you spend on depressurizing the slope you get $5 return in terms of better slope angles and/or improved performance”.

Mining is a very dynamic and global industry. It is fair to say that Canada, USA, Australia, South Africa, Chile and Russia are the leading “mining” countries. Generally speaking, mining costs have been rising and head grades falling over the past few years. For instance, Chilean copper mining costs have tripled over the last decade. While the cost of labour represents a major increase, energy is the key determining factor of this increase. The decrease in ore grade is associated to aging mining operations as new deposits are becoming increasingly difficult to commission because of increasingly difficult and lengthy environmental permitting processes, combined with the difficulty and cost to supply energy and water.

Based on Wood-Mackenzie (2015) C1 cost data, Teck’s CBU ranges from Tier 2 and Tier 3, respectively for Cu annual output and production costs at HVC and Chilean operations Figure 3-8. This suggests that companies that cannot capitalize on economies of scale to reduce their copper production cost, and must compensate by operational discipline and excellence to reduce/control the C1 cost. Teck falls within this category, which means the company's financials are moderately to highly sensitive to unit production costs, which is indirectly related to the market fluctuations of copper price.

Figure 3-8**:** Global cost position for selected Teck mines.



	Safety (HPI Freq)	Copper (tonnes)	Zinc (tonnes)	Moly (pounds)	Gold (ounces)	C1 Cash Cost (US$/lb Cu)
Highland Valley		121,491	-	5,163,300	4,806	$1.65
Duck Pond		14,177	16,185	-	2,922	$2.26
Quebrada Blanca		48,050	-	-	-	$2.26
Carmen de Andacollo		71,797	-	-	47,499	$2.04
Antamina (22.5%)		77,597	47,482	706,100	-	$0.59
Teck Copper Actual		**333,112**	**63,666**	**5,869,400**	**55,227**	**$1.61**
Teck Copper Plan		**341,177**	**61,685**	**7,121,417**	**48,560**	**$1.74**
		-2.4%	**+3.2%**	**-17.6%**	**+13.7%**	**-7.5%**

(Sources: C1 cash cost, Teck 2015b; Wood-Mackenzie, 2015)

The largest copper mines in the world are located around porphyry deposits found along the Pacific Ring-of-Fire belt, with Chile and British Columbia representing the focus of short- to mid-term new projects in the global copper pipeline. As discussed in section 2.1, new projects in Chile typically extract seawater and construct large and costly desalination plants that carry high pumping costs related to power, and expensive infrastructure.

More locally in BC, the recent release of the Mount Polley Independent Review Investigation on the August 2014 tailings dam breach has brought an avalanche of changes to future regulation regarding the permitting and operation of tailings dams. The main recommendations of the Review Panel offered to the BC Ministry of Mines, Petroleum and Energy (BCMMPR, 2015) call for more stringent designs and inspection of existing and future tailings impoundments (aka higher costs). The Panel also recommended the use of Best Available Practice in tailings management technologies (e.g. thickened or paste tailings), which could increase water recovery (dewatering prior to tailings deposition) but at higher operating and capital costs (Davies & Rice, 2004).

Perhaps the over-riding current trend in mining lies in the push towards sustainable mining which, in addition to making environmental sense, also steers companies to maintain or improve their license to operate. Any proposed Greenfield or expansion mining projects needs to go through a Social & Environmental Impact Assessment (SEIA) study to obtain mining permits/licenses. A company with a strong reputation in sustainability such as Teck can accelerate the regulatory process due to good standing with authorities.

3.4 Benchmarking

This section of the study attempts to benchmark the water usage of the three Teck sites considered versus the mining industry. Climatic, operational, regulatory or other factors were not accounted for this benchmarking exercise, i.e. it is a “cold” comparison. Table 3-4 compares relative “water usage performance” for the three Teck open pit mines considered. The indicators most commonly used in the industry are water reclaim rate (as a % or m^3/T mineral produced) and make-up water usage (m^3/T mineral produced). As an example, Figure 3-9 presents the estimated make-up water requirement for the QB2 project (Choja tailings impoundment) benchmarked against other large open pit copper mines in Chile (Golder, 2012). Although the projected make-up water requirement for QB2 is fairly poor at 0.62m3/T, it appears somewhat average compared to other large open pit copper mines such as Collahuasi or Escondida located in the Atacama Desert.

Table 3-4**:** Comparison of water usage efficiency for three Teck sites.

Parameters	**Units**	**THVC[1]**	**QB2[3]**	**CdA[2]**
Water Consumption	m^3/year	71,899,117	43,800,000	43,167,640
Reclaim water	m^3/year	58,238,285	13,140,000	32,707,600
Make-up water	m^3/year	13,660,832	30,660,000	10,460,040
Water per tonne Cu produced	m^3/t	1.46	0.89	2.15
Make-up Water Unit Consumption	m^3/t	0.28	0.62	0.52

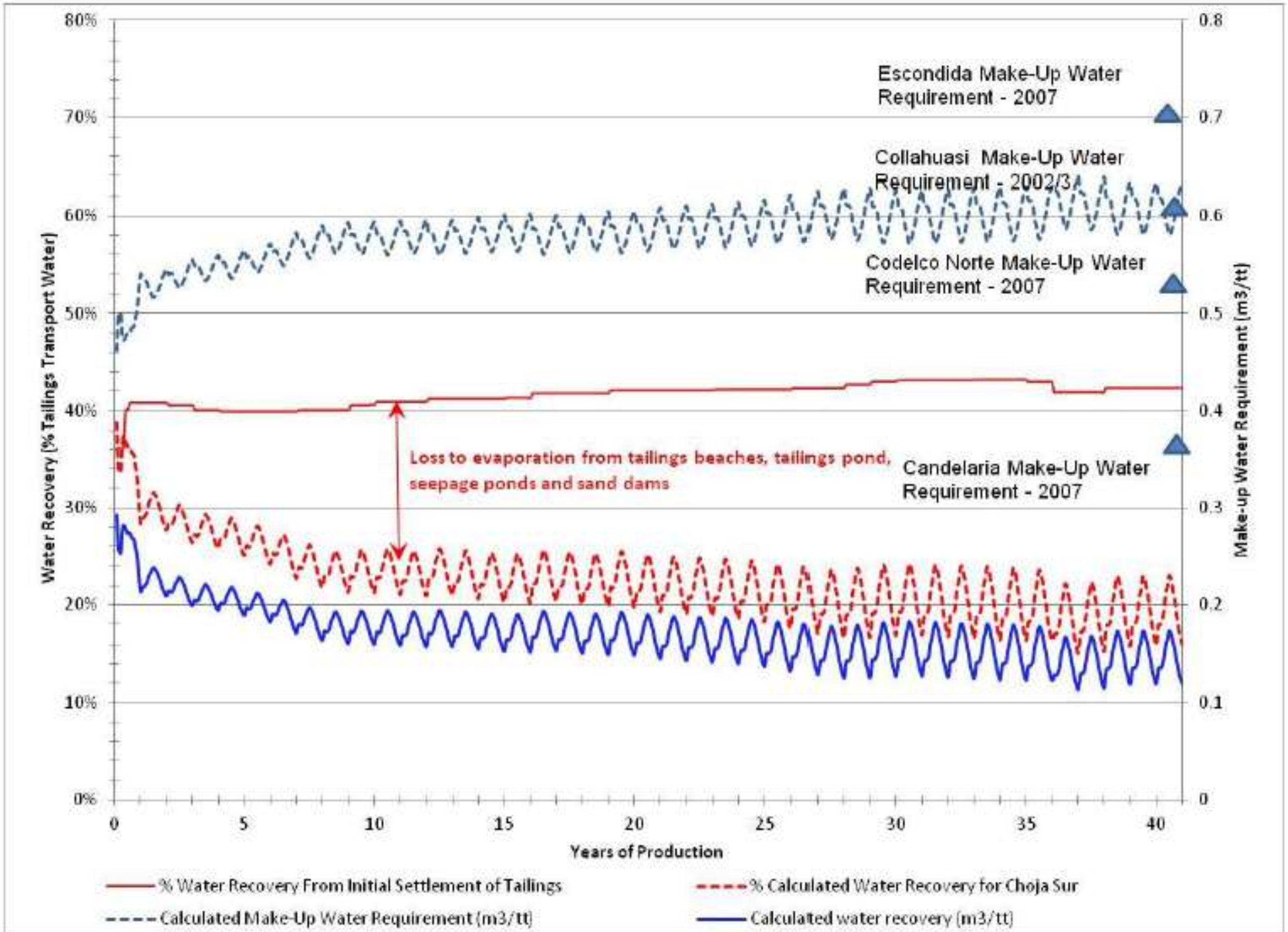
Table 3-5 presents some preliminary benchmarking results for the three selected Teck's mining operations against the industry. Figures 3-10 and 3-11 graphically illustrates the key variables, showing upper and lower industry ranges .The water usage performance is rather difficult to benchmark mainly due to the difficulty in gathering proprietary information from mine sites, including the unit costs for power, make-up water and/or mineral productions as well as the consumption rate of make-up water. The level of investment of a given company towards pit dewatering activities is generally unknown, and so is the degree of efficiency of these systems. In addition, the financial impacts of groundwater on mine operations activities are mostly guarded and not directly or publicly available.

For these reasons, much of the benchmark data gathered in table 3-5 has been collected through the experience of consultants and/or the review of technical papers. In most cases, the specific mine sites were not referred to directly, e.g. "a mine site in northern Chile". This illustrates the sensitive nature of the water-related information, both from a financial and image or perception perspective. Nevertheless, a number of conclusions can be derived from Table 3-5.

Firstly, the tailings pond water reclaim rates are very low (consistently <50%) in Chile due to evaporation. THVC essentially exemplifies best practice in terms of water reclaim from the TSF. The only mine sites with higher reclaim rates are located in the Arctic, where evaporative losses are minimal. However, THVC uses a large amount of water per ton of ore produced, the old adage "the more you have the more you spend". In comparison, make-up water requirements for Teck's mine in Chile are near the higher end of the range at 0.7m^3/T which, combined with high cost of electricity results in very expensive make-up water (2-4 times more than HVC). Pit dewatering also does not appear to be considered or identified as a strategy for make-up water supply for Teck's mine in Chile. The over-arching conclusion from Table 3-5 is that the impact of water on mine operation costs can be significant.

.

Figure 3-9: Estimated make-up water requirement for QB2 project benchmarked against other large open pit copper mines in Chile.



(Choja tailings impoundment, source: Golder, 2012).

Table 3-5**:** Preliminary benchmarking results for Teck mines against the industry.

					Typical Industry Range			
Benchmarking Parameter	**Units**	**THVC**[1]	**QB2**[3]	**CdA**[2]	**Min**	**Max**	**Example**	**Site**
Reclaim rate	%	81	30	76	30	90	90	Diavik, Canada
Reclaim rate	m^3/t	1.18	0.27	1.63	0.4	1.7	0.35	Escondida, Chile
Reclaim cost	$\$/m^3$	0.11	0.58	0.91	0.1	1.5	0.10 1.50	Candalaria, Chile Andina, Chile
Make-up water cost	$\$/m^3$	0.57	2.36	1.44	0.5	3	4.5	Escondida, Chile
Groundwater cost	$\$/m^3$	0.38	-	-	-	-	0.25	Round Mountain, Nevada
Desalinated water cost	$\$/m^3$	-	2.36	-	-	-	4.5	Escondida, Chile
Water per tonne Cu produced	m^3/t	1.46	0.89	2.15	-	-	1	Laguna Seca, Chile
Make-up Water Unit Consumption	m^3/t	0.28	0.62	0.52	0.4	3.0	2.5 4.0	FMI mine, Arizona KGMH mine, Poland
Contribution of open pit dewatering to plant water usage	%	18.0	3.0	4.3	0	100	-	-
Mine Operations impact of groundwater in the open pit	$/year	8,000,000	-	-	-	-	50,000,000 4,500,000	Goldstrike, Nevada Collahuasi, Chile

Figure 3-10: Unit rate water consumption of three Teck sites against industry range.

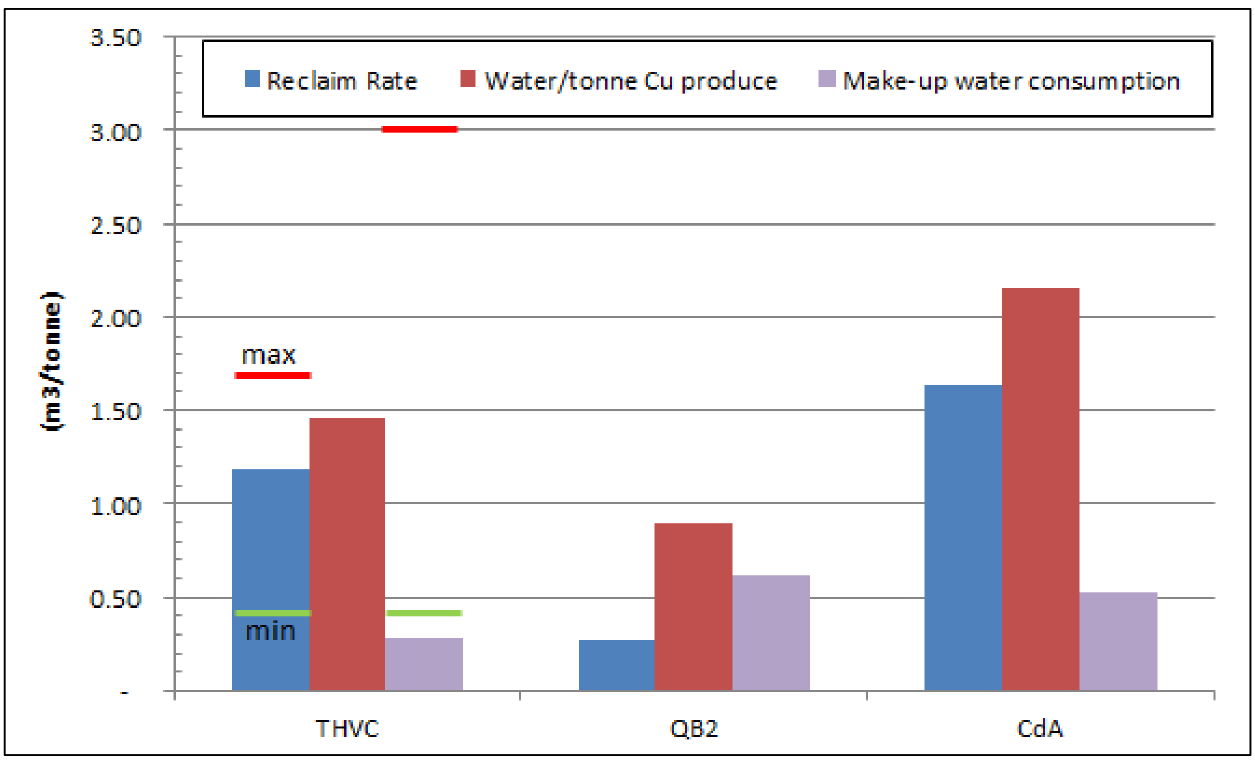
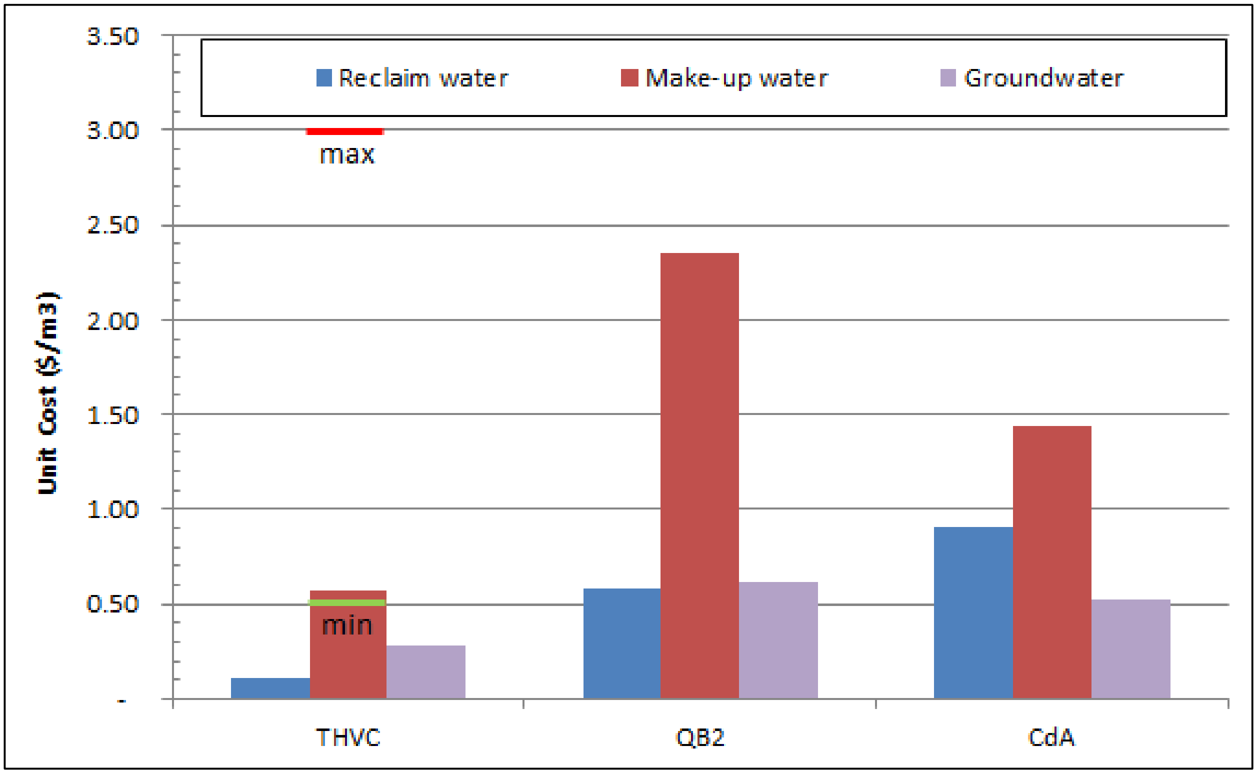


Figure 3-11:Unit water costs for three Teck sites against industry range.



4: Teck's Water Management Options

This chapter explores some potential water management options that could lead Teck to reduce both mining operating costs related to water and the consumption rate of fresh make-up water. Site-specific options are presented for HVC, CdA and the QB2 project based on the particular challenge (s) experienced at these sites. A high level strength-weakness-opportunity-threat (SWOT) analysis is also presented in an attempt to frame the situation of the company relative to the financial and sustainability impacts of water for the Teck operations considered.

4.1 Gap Analysis

Within the last several years, Teck has made significant effort in improving water stewardship within the company. The addition of water-related staff position, the creation of IWMP's, and the elaboration of water-related corporate sustainability objectives are only a few examples of the intent of the company to improve water management. There is still a need to improve however. A gap analysis is a simple, yet useful method to determine areas of improvement. A "gap" is defined as the difference or the space between a defined target level of practice versus current level of practice. These identified gaps represent areas of risks or opportunities.

Teck's sustainability strategy (Teck, 2013) includes the following six elements: water, energy, biodiversity, people, communities and material stewardship. Therefore water management in the mines is nearly associated to all sustainability categories. While key objectives of the sustainability strategy pertain to reductions of energy and water consumption, these objectives rather vague relative to the definition of specific reduction levels. For this reason, preliminary targets were identified for energy and water consumption, and unit cost of make-up water based on the above discussion. Table 4-1 summarizes these proposed target levels and associated gaps related current level of water management for the three Teck sites considered. The key message of Table 4-1 is the need to obtain make-up water locally and at a cheaper unit cost for CdA and increase water reclaim rate. The proposed target levels are based solely the professional judgement of the author for nominal, achievable reductions in volumes and/or consumption levels, as well as improvement of efficiencies.

Following the identification of gaps, the next logical step in assessing the water challenge at Teck is to develop options to mitigate the impacts and raise the level of water management from a mine operations point of view.

Table 4-1**:** High level GAP analysis of Teck's water usage and impacts to mining activities

GAP	Current Situation	Desired "Target" Situation
1	Average reclaim water rate Ranging 30-80%	Average reclaim water rate >50%
2	Haul trucks carrying blasted ore rock with up to 5% water content	Water content in blasted ore <2%
3	Make-up water costs up to 5 times the cost of reclaim water	Obtain water locally to match unit cost of reclaim water
4	Decreasing allowance for water licenses vs. increase demand for water	Decrease water requirement
5	Rising energy and infrastructure cost to obtain make-up water	Decrease water requirement and obtain at lower cost locally (open pit)

Table 4-1 highlights the main findings found in section 3 which forms the basis for developing potential water management options for the three Teck sites considered. For any of the site, options should meet or combine the following objectives:

- reduce the quantities of freshwater make-up used for the mining process;
- reduce the cost unit cost of water required for ore processing; and
- reduce the impact of water on mine operations, i.e. reduce mining costs associated with water-related mining inefficiencies.

Due to the relative wide spectrum of the issue at hand, each of the three sites was first analyzed "macroscopically" to identify areas for up-side, i.e. where are the value drivers relative to water. These drivers can be described as follows:

A. <u>THVC:</u>

    1. Increase pit dewatering to reduce impacts on mine operations due to abundance of groundwater in the open pits;

2. The reclaim rate at the TSF is already over 80% so limited upside. However, use available storage in TSF to increase water supply.
3. Improve energy efficiencies (low energy cost but high energy consumption)

B. CdA:

1. Take advantage of groundwater potential in the open pit to reduce make-up water requirements from the Elqui Valley;
2. Improve reclaim rates at the pond and decrease cost of reclaim water;
3. Find alternate source of make-up and/or reduce cost of electricity consumption related to water (cost).

C. QB2:

1. Limited groundwater potential in the open pit, so the objective should be to maximize reclaim and recycling of water;
2. Reduce cost of electricity and electric consumption

This "mind frame" was then used to develop the options listed in Table 4-2. In addition to these blue-sky options, the integration of open pit dewatering activities into Teck's IWMPs is considered a low hanging fruit to provide a reliable and economic source of make-up water, i.e. at least for THVC and CdA where a considerable groundwater potential exists. These options were organized into three water management categories: (i) groundwater management, (ii) surface water management, and (iii) TSF water management. The following sections briefly describe each option.

Table 4-2**:** Summary of options potential mine water management improvement options.

Category	THVC	CDA	QB2
Groundwater Management	Maximize open pit dewatering	Maximize open pit dewatering	N/A
Surface Water Management (& transportation)	Research the availability of installing an electricity generation device in the gravity line that flows from the Reservoir to the Million Gallon Tank.	Fog water and rain water harvesting for communities below the mine to assist with agricultural needs	Waste water re-use by electrochem-RO (reverse osmosis) technology
			Fog water harvesting for Pintado and other communities near the Choja TSF site
			Build a solar panel farm
TSF Management	Establish tailings deposition plan, improve pond management with additional discharge points to avoid having to run Spatsum	Build a solar panel cover over the tailings pond (reduce evaporation and generate electricity)	Favor S-21 TSF over Choja Sur due to (i) shorter pumping distances, and (ii) steeper valley
	Short-circuiting of the tailings water reclaim pipeline to reduce pumping travel distance (energy cost)	Eliminate reclaim water trenches ("zanjas") and replace with inclined pipe	
		Increase density of tailings from the thickener (i.e. solids content by wt) to extract more water	

4.2 Groundwater Management

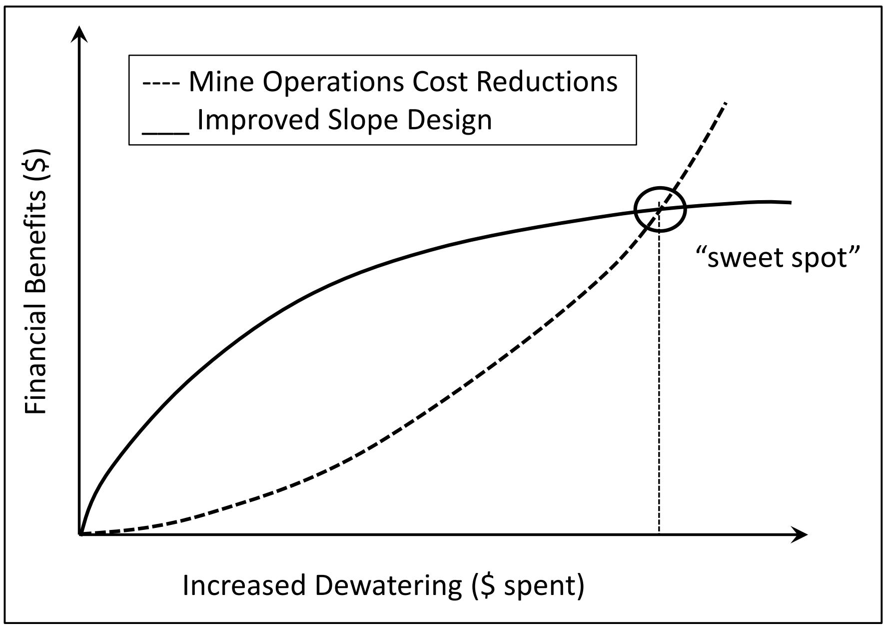
The following sub-sections examine the groundwater management aspects of HVC, CdA and QB2. As discussed below, significant amounts of groundwater found at HVC and CdA need to be exploited adequately. The management of groundwater at Teck's open pit mines generally encompasses two principal aspects within the frame of the current discussion:

1) The impact of groundwater to mining operation activities, i.e. "wet mining" both in terms of efficiencies and costs, as well as impact on mine design (slope angles); and

2) Pit dewatering as a source of make-up water for the process plant.

Active pit dewatering can address both of these aspects. However, the difficulty lies in "how much to invest towards dewatering"? The spending should ideally balance with incurred benefits. In other words, there is a point of diminishing returns related to the benefits of groundwater management spending. As illustrated in Figure 4-1, there exists a point where increased expenditures on dewatering activities do not benefit the mine in terms of reducing mining inefficiencies related to the presence of groundwater. The alternate scenario could be that a mine would need to spend excessively to extract groundwater from the pit as a source of make-up water. Therefore, a cost benefit analysis needs to be carried out to "size the pie".

Figure 4-1**:** Recommended level of dewatering effort, balancing incurred benefits with spending.



4.2.1 Highland Valley Copper (HVC) Mine

The current combined groundwater inflow from THVC's three active pits is around 6,500 USGPM and has to potential to increase to ~9,000 USGPM by 2016 (M. Veillette, pers. Comm., May 20, 2015). This could translate into a 7% increase in contribution of groundwater to the overall site water consumption for ore processing. This increase is more than sufficient to off-set the need for other make-up water from the Thompson River, which would be economically advantageous since the Spatsum pump house is very expensive to operate (Table 3-2).

The infrastructure required for this step-up in pit dewatering will be substantial. However, given the negative operational impact of groundwater in the pits, combined with the above-mentioned advantage, it is concluded the continued investment in pit dewatering measures at THVC is not only justified but necessary. These enhanced dewatering measures are considered particularly critical due to the increase depth in the pits (more and more water) and the associated longer, more expensive hauls.

4.2.2 Carmen de Andacollo (CdA) Mine

CdA currently operates a total of eight pumping wells in the open pit, which have a combined capacity of 50L/s corresponding to approximately 10% of annual site water consumption. However, the utilization rate of these in-pit wells has historically been quite poor, averaging 50-60% on a monthly basis. Only two to three wells per month are typically used, while the others are down for maintenance or other reasons, which translates to a pit groundwater contribution of <5% of overall site water consumption. While this poor availability does not really impact mining operations and/or pit slope stability, the economic benefit of cheaper local groundwater is not realized.

The CdA water balance indicates a contribution from the wet ore of 29L/s, which implies a water content of about 4.5%, i.e. significantly higher than what is recorded at HVC or QB. This water extraction rates is equivalent to approximately half from what the in-wells are producing are producing, although at a considerably higher unit cost. It would be cheaper for CdA to extract the water contained in the ore-bearing rock by operating additional wells than instead of the current extraction using energy-intensive filter presses at the process plant. The extent of the potential saving is not clear because the accurate unit cost of water pumped from the pit is unknown at this time.

A recent groundwater flow model (SWS, 2015) indicates a potential to increase pit dewatering production to beyond 60L/s, thus a potential to reduce make-up water requirement by 10L/s or over 300,000m^3/year reduction from the Elqui River. Assuming the local pit water is produced at half that of the Elqui water, this translates to a reduction of $225,000/year in pumping costs. The Geotechnical Review Board (GRB, 2015) indicated that the groundwater potential from the open pit over the next three years is likely over 100L/s, and that deep pumping wells could serve to intercept seepage from the TSF that otherwise joins the groundwater system. This represents a two-fold increase with corresponding annual savings potentially over $1M/year compared to current make-up water. It is thus strongly recommended that CdA invests in aggressive pit dewatering measures.

4.2.3 Quebrada Blanca 2 (QB2) Project

As previously mentioned, Teck’s QB2 project is located at high elevation in the Atacama Desert. Previous hydrogeological studies estimate the groundwater potential of the open pit to ~30L/s (Artois, 2012), which represents only about 3% of the site process water consumption (Table 3-2). The presence of groundwater in the pit is not predicted to impact mining operations, but rather reduce pit slope stability. For this reason, the development of the pit will need to include depressurization measures.

Other aquifers around the project site are heavily regulated for environmental concerns and thus not available as a potential groundwater source for the project. In summary, there is very limited groundwater potential for use as make-up water for the QB2 project due to the geographical and geological setting of the site. For these reasons, other water supply and management options for QB2 will be explored in the next sections.

4.3 Surface Water Management

This section investigates management options related to surface water. Energy costs and efficiencies pertaining to water transportation to transportation of water are also discussed. Water stored at tailings storage facilities (TSF) is addressed as a separate topic in section 4.4.

4.3.1 Highland Valley Copper (HVC) Mine

HVC manages surface water very effectively and sends the collected waters to the mill via either the TSF or the Witches Brook Pump House (WBPH). However, the current system could be improved to reduce pumping costs. The review of the site water balance (AMEC, 2013) and relative energy expenditures (Rojas, 2012) led to identify two improvement options:

1) Research the availability of installing an electricity generation device in the gravity line that flows from the Reservoir to the Million Gallon Tank (MGT).

2) Re-route the surface and groundwater collected at the Highmont pit to send the water directly to the MGT instead of the current longer downhill to the MWPH and then back up to the mill.

4.3.2 Carmen de Andacollo (CdA) Mine

The collection of fog water was identified as a potential local source of make-up water for CdA. Similar to the physiographic arrangement of British Columbia, a coastal mountain range stretches across Chile for thousands of kilometers along the North-South axis between the Pacific Ocean and the Andes. The coastal mountain (elevation < 1,200m) intercepts the moisture from the ocean and creates foggy weather conditions for a good part of the year. In fact, fog is so common in the city of La Serena that it hosted the 4th International Conference on fog, fog collection and dew in 2007.

Fogquest (www.fogquest.org) is a non-profit, registered Canadian charity dedicated to planning and implementing water projects for rural communities in developing countries. Between the early nineties until 2007, they collaborated in Chile with the National Forestry Corporation (CONAF), the Catholic University of the North, and the Catholic University of Chile to develop small-scale fog collection projects for coastal communities. *El Tofo* was FogQuest's largest project, which ran between 1987-2002 just North of La Serena, Chile. The project consisted of 50 large fog collectors (LFC) of 50m^2

each, which produced an average 15m^3/day of water for agricultural and drinking use, with peaks of 100m^3/day. An average production cost of $1.40CAD/m^3 was reported (http://www.oas.org/dsd/publications/unit/oea59e/ch12.htm), which is similar to the current cost for make-up water at CdA (Table 3-2). The total cost of the project was estimated at $120,000 (2007 CAD).

Capturing water from fog is very simple and typically involves rectangular obstacles constructed of polypropylene mesh placed perpendicular to the prevailing flow of the clouds. Drops of water collect on the “fog harvester”, coalesce, and flow by gravity along a plastic conduit at the bottom of the mesh to a receptacle (tank) for later treatment (if required) and distribution. Experimental projects conducted in Chile indicate that it is possible to harvest between 5.3 L/m^2/day and 13.4 L/m^2/day depending on the location, season, and type of collection system used. The *Atrapeniebla* brewery of La Serena uses this technique to collect the water for their sustainable beer.

For CdA, a reduction of 1% of make-up water translates to about 277m^3/day, which is about 3 times larger than the *El Tofo* peak production. As a preliminary estimate, a surface of approximately 2ha (20,000m^2 of LFCs) would be required to provide this flow reliably for an approximate capital investment of about $1M. Assuming a unit production cost similar to current values, Teck would need to evaluate the extrinsic value of a 100,000m^3/year (1%) reduction in water pumped from the Elqui valley. In summary, this option is more attractive from a sustainability advantage than a financial one.

4.3.3 Quebrada Blanca 2 (QB2) Project

The site water balance (Golder, 2012) and the feasibility report (Teck, 2012) were consulted for this study. This reviewed allowed to identify two potential options for QB2 to generate local water and slightly reduce make-up water requirements. Although this assessment is preliminary, the options are considered marginal to moderate from a value-added perspective.

<u>Options 1:</u> Water treatment re-use (reverse osmosis)

The QB2 mine will employ close to 2,000 employees plus contractors at any given time (Teck, 2012). The current plan to manage waste water is to use conventional septic tanks installed in series with assigned residence time. However, other technologies such as reverse-osmosis (RO) exist that can render waste water useful for other purposes, such as process water for mining (www.saltworkstech.com).

Although this current research has not investigated the capital and/or operating costs of RO systems for QB2, it appears that a single-line RO system could process up to 325m^3/day of waste water. This flow corresponds to only about 0.5% of daily make-up water requirements for the QB2 plant. Nevertheless, it is postulated that the feasibility and economics for using such a technology be studied in further details given the very limited water supply options for this project and the relative high unit cost of make-up water.

Option 2: Fog water

As the QB2 mine is located at over 4,000masl elevation in the Andes, therefore fog water collection is not an option at the site. However, a number of communities such as Pintado (near the highway turn-off) and Huatacondo (near the Choja Sur TSF) impacted by the project live at lower elevations between 1,200-2,000masl, in areas that experience foggy periods. Although fog water could not be collected in any amount sufficient to make a difference for the QB2 plant, it could help these communities living in water-stressed environments. These communities presently obtain their water by truck delivery via a utility provider at a high cost. Therefore, an investment by Teck towards the construction of fog water collectors could positively impact these communities and improve, or reinforce existing relationships.

4.4 Tailings Management

As sadly exemplified by the August 2014 tailings breach at the Mt. Polley mine, BC, the traditional way of disposing tailings into impoundment carries a relatively high level of liability and is not considered “Best Practice” (BCMMPR, 2015). In comparison, other tailings technologies such as thickened or paste tailings offer more secure ways of managing tailings, albeit at a higher cost, both Capex and Opex (Davies & Rice, 2004). Therefore it is primordial for mining companies to reconcile what they are willing to pay for water and tailings, versus what the investors are willing to pay for stocks in a sustainable company. Teck investors do not necessarily look for the highest return but rather at a leading Canadian mining company that “does it right”. In other words, they have a higher willingness-to-pay (WTP) and accept the trade-off offered by sustainable mining.

Due to the high capital costs involved in building and operating their respective TSF, it is unrealistic to consider that either THVC or CdA could easily or economically convert their tailings management technology to another. Similarly, conventional tailings disposal was selected as the preferred technology for QB2 during the Feasibility Study, mainly due to costs and risks related to other non-proven technologies at the scale of QB2 production (Golder, 2009). These operations thus appear “committed” to long term tailings storage in impoundments. For this reason, this section intends to identify a few potential areas of operational improvement of the TSF, rather than proposing changes to tailings disposal technologies.

4.4.1 Highland Valley Copper (HVC) Mine

This section proposes operational improvement measures of the tailings storage facility (TSF) at HVC which could reduce operational risk and/or costs. Figure 2-1 presents an overview of the HVC TSF, which is comprised of the LL and HH dams. HVC and its predecessor operating companies have operated this facility for over 30 years and it currently one of the largest TSF in North America. A dynamic schedule of dam construction and raises was initiated in 2008 in response to the approval of the latest life-of-mine (LOM) plan to 2026.

For several years now, a single discharge point has been used to deliver tailings to the impoundment, which seriously reduces the flexibility and ability to manage the pond efficiently. The situation has become critical since the end of 2014 to a point that the current reclaim system can barely maintain physical access to the pond. The concern to lose access to the pond is such that the Spatsum pump house is planned to re-start operation in Q2 or Q3-2015. From a water management perspective, this situation is detrimental to THVC since it will trade reclaim water at ~$0.11/m^3 with river make-up water at ~$0.57/m^3.

A formal tailings deposition plan that includes multiple discharge points should be developed to allow HVC to operate the TSF more efficiently and avoid relying on the Spatsum station for make-up water. A technico-economic analysis for this proposed improvement has not been carried out within this project. However, it is the author's opinion that it would be both economic and beneficial to HVC given the remaining mine life and potential LOM extensions.

4.4.2 Carmen de Andacollo (CdA) Mine

CdA is currently investigation the possibility to increase the density of the tailings in order to increase water recovery from the thickeners. Beyond this concept, the review of the TSF operational manual (AMEC, 2008) and online literature allowed the author to identify two potential options to increase reclaim water recovery from the TSF and generally decrease the cost of water for CdA. This section hence focuses on reducing CdA's operating costs related to the management of the TSF and its water.

<u>Option 1:</u> Floating solar panel farm

As discussed in section 3.1, the CdA TSF suffers from extremely high evaporation rates. At the same time, make-up water from the valley is relatively expensive (Table 3-2). The construction of a solar panel plant floating on the tailings pond is considered an exciting solution to this dual challenge. On the one hand, the solar panels would generate electricity that could potentially offset the high cost per kWh.

On the other hand, the solar panel cover over the pond would greatly reduce the evaporation losses, thus increasing reclaim rates at the TSF.

A floating solar plant was constructed in Jamestown, South Australia in 2015 at a cost of $12M AUS (www.infratechindustries.com). Although the technical specifications of this plant are not available at this point, it is reported that (i) the solar panels are ~57% more efficient than typical land-based panels, due to the cooling effect of the water; and (ii) evaporation losses from the impoundment were reduced greatly since 90% of the pond is covered, which is predicted to save ~70,000m^3/year (http://www.abc.net.au/news/2015-03-05/australian-first-floating-solar-farm-for-sa/6281374).

On average, CdA operates the TSF with 300,000-600,000m^3 of water stored, which correspond to a water surface area ranging between 20-40ha. To put things in perspective, Sandfire Resources is currently building a 20ha solar plant at a copper-gold mine in Western Australia. The $40M AUS project consists of 34,000 panels and generates over 10MW electricity (http://www.abc.net.au/news/2015-02-12/juwi-to-build-solar-plant-at-sandfire-mine-in-wa/6086856). Assuming that a land-based foundation for a solar panel is roughly the same cost as a floating foundation, these values can be used to provide a high level cost estimate for a floating solar plant at CdA. Since reclaim water at CdA is roughly 50% cheaper that make-up water ($0.91/m^3 versus $1.44/m^3), a floating solar farm that could reduce evaporation losses by a nominal 50% appears to be a very interesting proposition.

<u>Option 2:</u> Elimination of the clear water trenches ("*zanjas*")

Figure 422 shows an overview of the layout of the trenches pre-excavated above the TSF pond to collect the supernatant water as the pond level rises. The TSF design includes a total of 13 of these trenches, each constructed at a cost of ~$1M. Trenches no. 10-13 have not been excavated yet and will not be needed until 2018 or so. Therefore, it is worth considering alternative pumping technologies. The use of a portable inclined pipeline to lower a turbine pump is considered such a potential alternative (Figure 4-3). While a technico-economic analysis has not been carried out as part of this study, it is likely this system would cost considerably less than $4M, i.e. the cost for trenches no. 10-13. This option should be evaluated in further details.

Figure 4-2**:** Current reclaim water system at CdA

Image reproduced from Google Earth (2013)

Figure 4-3**:** Potential modification of reclaim water system at CdA.

(Photo reproduced from the Flowserve Corporation website; www.flowserve.com)

4.4.3 Quebrada Blanca 2 (QB2) Project

The Atacama Desert is one of the premium places in the world in terms of solar radiation, both in terms of intensity and number of days per year. Facing similar challenges as Teck related to high energy costs in Chile, Antofagasta Minerals (AMSA) constructed a large solar power plant in 2011consisting of over 16ha of solar panels at its Tesoro copper oxide mine, near Antofagasta, northern Chile. The project represented investments of over $14M USD commenced operation in 2012 and generates over 25MWh/year. This new source of local energy provides approximately 55% of required power on site, and allowed AMSA to decrease annual diesel consumption by 17% and reduce its carbon footprint by 4% (*La Tercera*, 2011).

The construction of a solar panel farm for QB2 could partially offset the high cost and high consumption rate of electricity required for the desalination process and reclaim system from the TSF. Similar to other options proposed in this chapter, a technico-economic analysis for a QB2 solar plant has not been carried out as part of this study but would be interesting to consider. Nevertheless, the AMSA example suggests that solar energy can be produced in Chile at a competitive price compared to the private utilities grid. Given the high electrical demand for the QB2 project, solar energy should be considered to partially complement the current energy supply plan.

4.5 Summary of Options

This chapter presented a number of water management options that were identified for HVC, CdA and QB2. These options pertained to three water management categories, namely: groundwater management, surface water management (including transportation) and management of the tailings storage facility (TSF). Table 4-3 summarizes these options for each site and present the primary objective underlying any given option. An un-bounded "blue sky" thinking approach was used to develop these options, therefore certain options are inherently more realistic and/or offer better value than others. Chapter 5 intends to evaluate and quantify these options in more details.

Table 4-3: Summary of water management options.

No.	Options	Site	Water Management Focus	Primary Objective
1	Additional pit dewatering	THVC	Groundwater	Reduce mine OPEX
2	Power generation from MGT	THVC	Surface water/transportation	Energy efficiency
3	Re-routing HMT water to MG	THVC		Energy efficiency
4	Develop tailings deposition plan	THVC	TSF	Reduce OPEX and risk
5	Additional pit dewatering	CdA	Groundwater	Reduce water cost
6	Fog water collection	CdA	Surface water/transportation	Sustainability
7	Floating solar farm	CdA	TSF	Reduce water cost
8	Modification of reclaim system	CdA		Reduce OPEX
9	Additional pit dewatering	QB2	Groundwater	Reduce water cost
10	Waste water treatment (RO)	QB2	Surface water/transportation	Reduce water cost
11	Fog water collection	QB2		Sustainability
12	Solar panel plant (land-based)	QB2		Reduce OPEX

5: Assessment of Options

This section provides a high-level semi-quantitative assessment of the water management options identified in Section 4 for the three Teck mines considered. Within this chapter, the options are evaluated from a rather global Teck perspective, i.e. beyond the 2015 economic conditions. Evaluation criteria needed to be developed to allow comparison of these options, and identify the leading ones. The author exercised judgement to achieve this task. Risk and opportunities associated with current water management practice are also evaluated to provide some guidance for future improvements.

5.1 Evaluation Criteria

A few simple criteria were developed to evaluate the potential of the options proposed above to bring value to Teck from the perspective of (i) reducing operational cost impact of water in the mine, (ii) reducing the unit cost of water, and/or (iii) offering a sustainability advantage. These criteria are generally consistent with criteria employed by Teck for projects evaluation. Table 5-1 presents the evaluation criteria selected along with a brief description. It is worthwhile to note that likelihood of adoption (i.e. ease of implementation) for any give option was considered, but not selected as an evaluation criteria since no significant buy-in concerns were identified for those.

Table 5-1**:** Selected criteria for evaluation of options.

Evaluation Criteria	**Description**
1. Capital costs	Capex ($ CAD) to purchase and commission the proposed system. This may include engineering studies or others, training, R&D, etc.
2. Operation costs	OPEX ($ CAD/year) to run the proposed system. This may include maintenance and/or replacement cost.
3. Potential production	Corresponds to the increase in generation of alternate water sources (e.g. more reclaim water than base case) and/or the production of on-site electric power.
4. Cost reduction potential	Corresponds to the relative reduction in operating cost (e.g. mining cost) and/or reduction in unit cost of energy or water.
5. Sustainability advantages	Relative fit with Teck's sustainability strategy and 6 focus areas

Table 5-2 summarizes the ranking parameters defined for each of the evaluation criteria presented in Table 5-1. For each criterion, the range of values considered is such that a “HIGH” translates to a substantial step-change for the operation, while a “LOW” would be insignificant. For example, a HIGH capital cost has a threshold of $1M, which means this investment would require the approval of the Senior Vice-President (SVP) of the Copper Business Unit (CBU) at Teck. Given the operational experience of the author, the following general guidelines were used to define the range for each evaluation criteria:

1. Capital costs: Very Low is defined as “can be approved at the departmental level”, versus Very High, which would require a formal Acquisition Requisition process.
2. Operating Costs: Very Low is no impact, while Very High would represent >1% increment to current annual operating costs.
3. Potential Production: Very Low is negligible, while Very High is above 1% of current water or power requirement for a site (m^3/year or kWh/year).
4. Cost Reduction Potential: Very Low means “difficult to quantify/measure”, while Very High represents 1-10% saving from annual operating costs.
5. Sustainability Advantages: Low means no positive impact, while Very High corresponds to multiple advantages across several Teck sustainability focus areas.

A simple score value ranging from 1 (less attractive or desirable for Teck) to 5 (highly favourable for Teck) was used to evaluate the proposed water management improvement options for each of the three Teck sites under study. Note that scores for all evaluation criteria are un-weighted since they are considered of equal relative importance within the scope of this preliminary assessment. Based on these game rules, an option can obtain a maximum score of 25.

Table 5-2**:** Ranking matrix for options evaluation criteria.

		Range & Score									
Evaluation Criteria	**Unit**	**Very Low**	**Value**	**Low**	**Value**	**Medium**	**Value**	**High**	**Value**	**Very High**	**Value**
1. Capital costs	$	< 100,000	5	<250,000	4	<500,000	3	<1,000,000	2	> 2,000,000	1
2. Operation costs	$/year	< 25,000	5	<50,000	4	<100,000	3	<250,000	2	> 500,000	1
3. Potential production	m^3/year kWh/year	<100 <10,000	1	<1,000 <25,000	2	<100,000 <50,000	3	<500,000 <75,000	4	> 1,000,000 >100,000	5
4. Cost reduction potential	$/year	< 25,000	1	<50,000	2	<100,000	3	<250,000	4	> 500,000	5
5. Sustainability advantages	-	No real advantage	1	Some fit	2	Neutral	3	Advantageous	4	Multi-advantageous	5

5.2 Option Evaluation

A combination of professional judgement, previous site operational experience and "back-of-the-envelope" calculations were used to quantify the evaluation criteria in the absence of formal technico-economic assessments for any of the proposed options. As such, this options evaluation should be considered preliminary. Leading options will require more detailed assessment of their true value potential. Table 5-3 summarizes the scorecards for each of the twelve options presented earlier.

The two leading options from Table 5-3 pertain to additional pit dewatering (no. 5) and floating solar farm (no. 7), both for CdA. Considering the proximity of the town of Andacollo and the relative high cost of make-up water and power, it is somewhat intuitive that this assessment would point towards CdA. Fog water collection for CdA (no. 6) also appears an option worth exploring in further detail.

In addition, the results from Table 5.3 suggest that additional pit dewatering at THVC (no. 1) is a promising value driver for this site, i.e. within the resolution of this option evaluation. This link is primarily related to the significant impact of groundwater on open pit mining operations (section 3.2). These impacts, and consequently mining costs are expected become even more significant in the future as the pits deepen and haul truck cycle time (distance travelled) increases.

The most promising option identified for the QB2 project seems to lie in the development of solar energy. However, the economics of such a power plant are beyond the scope of this thesis. The QB2 project is a high capital cost project and the addition of $40M Capex to the project would require a strong justification.

Table 5-3**:** Scorecard and relative ranking of potential water management options.

No.	Options	Site	Criteria 1	Score	Criteria 2	Score	Criteria 3	Score	Criteria 4	Score	Criteria 5	Score	Total
1	Additional pit dewatering	THVC	5,000,000	1	<250,000	3	~5,000,000	5	>500,000	5	Neutral	3	**17**
2	Power generation from MGT	THVC	750,000	2	75,000	3	5,000	1	<100,000	3	Neutral	3	12
3	Re-routing HMT water to MG	THVC	500,000	3	1,500,000	4	<100	1	<100,000	3	Advantage	4	15
4	Develop tailings deposition plan	THVC	>1,000,000	1	>500,000	1	<500,00	4	>500,000	5	Multi	5	16
5	Additional pit dewatering	CdA	1,500,000	1	75,000	3	150,000	5	>500,000	5	Multi	5	**19**
6	Fog water collection	CdA	1,000,000	2	50,000	4	100,000	3	100,000	3	Multi	5	**17**
7	Floating solar farm	CdA	35,000,000	1	75,000	4	>100,000	5	>500,000	5	Multi	5	**20**
8	Modification of reclaim system	CdA	1,500,000	2	100,000	3	<100	1	300,000	4	Very low	1	11
9	Additional pit dewatering	QB2	2,500,000	1	250,000	2	90,000	4	400,000	4	Neutral	3	14
10	Waste water treatment (RO)	QB2	2,000,000	1	250,000	2	100,000	3	100,000	3	Neutral	3	12
11	Fog water collection	QB2	1,000,000	2	50,000	4	50,000	2	75,000	2	Multi	5	15
12	Solar panel plant (land-based)	QB2	40,000,000	1	1,000,000	1	>100,000	5	>1,000,000	5	Advantage	4	16

5.3 Risks & Opportunities

Based on findings from Section 3, combined with the familiarity of the mine sites, the current water management practice of THVC and CdA (both operating mines) was assessed via a formal gap analysis, i.e. a more detailed version than the high-level one discussed earlier in section 5.1. Within the scope of this project, the two most relevant areas of water management practice (i.e. groundwater and TSF water) were divided into a number of individual "elements" of practice. The current and target levels for each of these elements of practice were identified and described. Table 5-4 presents the ranking criteria used for each practice element. Within Table 5-4, the level of practice arbitrarily ranges from 0 to 5; where 0 would indicate that nothing is done (or conversely not needed), and a Level 5 would indicate "Industry Leader".

Judgement was used to develop a preliminary, but not excessively detailed list of 14 distinct elements that can be "pinpointed" for assessment. Any element for which the current level of practice is less than the target level of practice (i.e. there is a "gap") represents a risk (operational or financial) to the business. These risks (gaps) could be quantified via a formal risk assessment process using likelihood of occurrence and consequences using Teck's corporate guidelines. However, this assessment was not carried out within the present project. Appendix E provides the detailed summary of this gap analysis along with ranking details. Figure 5-1 and 5-2 present radar plots for the spectrum of THVC and CdA water management practice, respectively for groundwater and TSF water management.

The gaps identified by the results of Figure 5-1 indicate that further efforts should be expanded at THVC to (i) improve the reliability of the pit water balance, (ii) augment pit dewatering activities to reduce impact on mine operations and increase the mine contribution to make-up water, and (iii) assign a formal dewatering group to manage these initiatives, including the tracking of cost of water (and energy). Similarly, the results indicate that CdA should (i) invest in increased pit dewatering measures to produce make-up water, (ii) improve the reliability of the site water balance, and (iii) begin tracking the cost of groundwater.

With respect to TSF water management, the gaps identified by the results of Figure 5-2 indicated that THVC should prioritize the development of a formal tailings deposition plan to ensure reliable physical access between the reclaim water pumping system and the pond, and to improve the reliability of the water balance. For CdA, the results indicate that the mine should (i) improve the reliability of the water balance since water costs are high, (ii) operate the TSF to minimize evaporation from the pond and beaches, and (iii) reduce the unit cost of reclaim water.

Table 5-4**:** Criteria for assessing the level of water management practice for THVC and CdA.

ELEMENT		Groundwater			
CONTEXT		How does the site perform with respect to groundwater management?			
LEVEL OF PRACTICE		**DESCRIPTION**	**THVC**	**CdA**	
0	Nothing or Not Applicable	Not done.			Ad-hoc and reactive
1	Minimum Practice or Requirement	Meeting minimum criteria to keep operating.			↓
2	Standard Practice, Below Average	Reactive, ad hoc application, basic management, some sort of plan in place, some infrastructure			↓
3	Standard Practice, Above Average	Consistent application, formal plan and budget in place, sufficient infrastructure and staff to minimize impact			↓
4	Industry Best Practice	Proactive, consistent application, robust plan, accurate and timely data, frequent review and improvement of process, target KPIs established			Planned and proactive
5	Leading Practice and Innovation Opportunities	As for Level 4 but typically involves use of complementary and/or alternate technologies to optimize the process to lower costs or wedge a business advantage.			

Figure 5-1**:** Radar plot of THVC and CdA groundwater management spectrum.

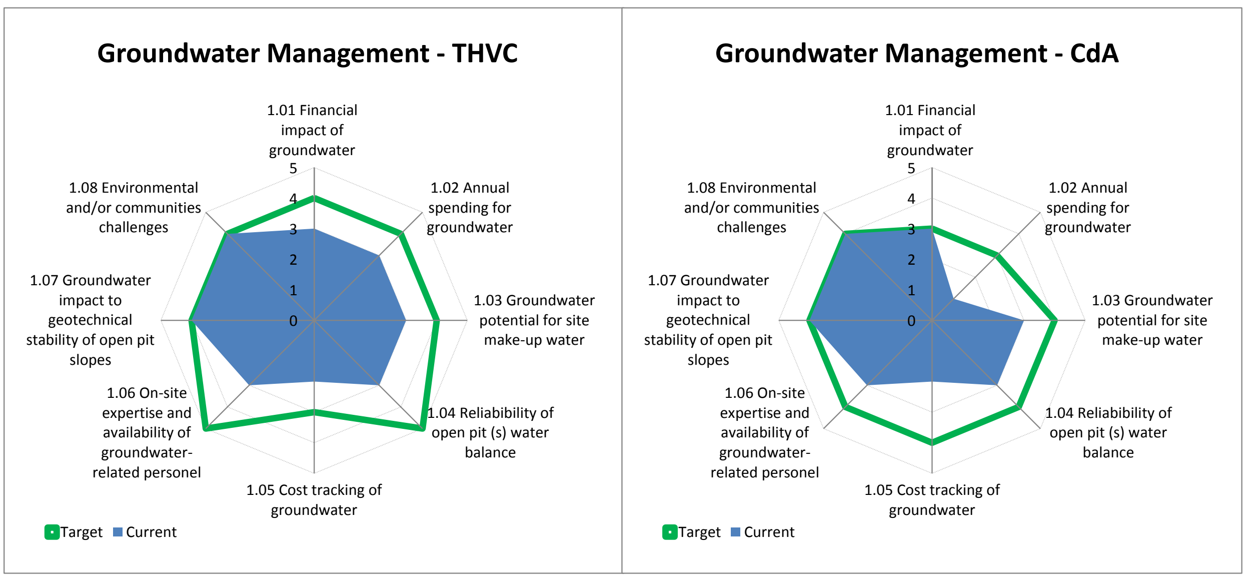


Figure 5-2: Radar plot of THVC and CdA TSF water management spectrum.

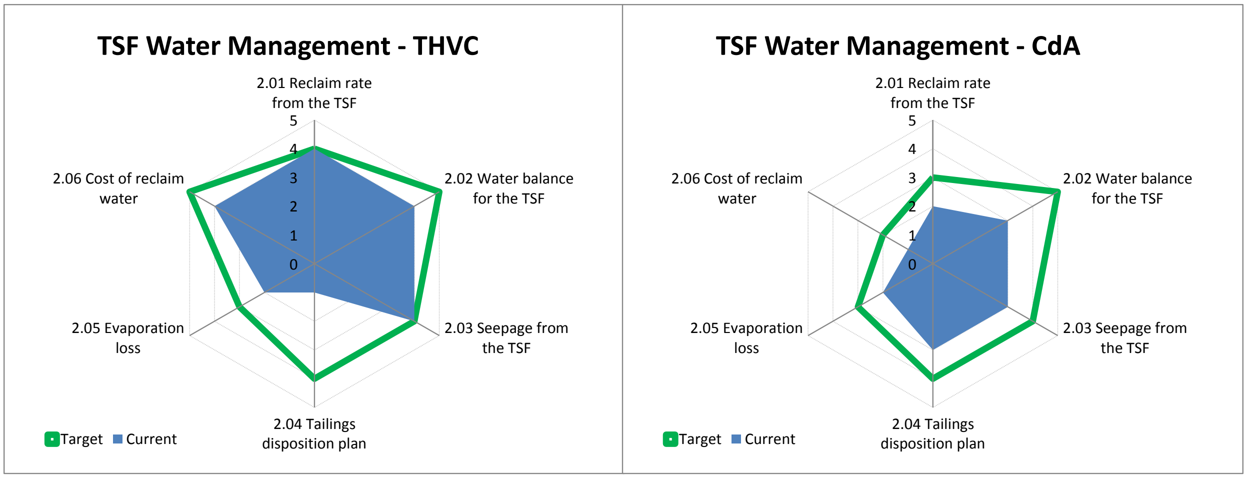


Table 5-5 presents a high-level strength-weakness-opportunities-threat (SWOT) analysis for Teck's mine water management in light of the gaps identified by the radar plot analysis above. The main threats identified pertain to probable upcoming changes in water regulations both in BC and Chile, which could complicate and increase the cost of make-up water. This situation could be exacerbated by any increase in electrical (pumping) costs. A deterioration of copper market conditions could render Teck more vulnerable to any combination of these situations.

On the other hand, Teck benefits from strong operational discipline and internal know-how. These attributes set Teck in a positive situation to evaluate and commission potential options that could allow the company to capitalize from an array of cost reduction, productivity increases, and sustainability opportunities.

Table 5-5: SWOT analysis - Teck's practice with respect to mine water management.

Strengths	**Weaknesses**
Corporate sustainability policies	Complexity of systems
Expressed sustainability goals	Difficulties to quantify water and costs
Internal know-how	Range of geographies and climates
Top 100 sustainable company	Oligopoly of electricity in Chile
Operational discipline	
Opportunities	**Threats**
Increased haul truck productivities	Pit slope instability
Technologies (pumps and motors)	Change in regulations (water volumes)
Lower mining costs (e.g. blasting)	Tailings dam instability
Lower maintenance costs	Complaints from communities
Lower water costs ($/m^3)	Increase in electricity costs in Chile
Reduced TSF evaporation rates	Metal market conditions ($/lbs Cu)
On-site electricity generation	
Collaboration from communities	

5.4 Summary

A number of evaluation criteria were developed in this section to allow a comparison between the twelve water management options identified in Chapter 4. These options were evaluated based on the criteria, namely: (i) capital costs, (ii) operation costs, (iii) potential reduction in water or power requirements, (iv) cost reduction potential, and (v) sustainability advantages. Enhancing pit dewatering activities and the construction of a floating solar plant were the two leading options identified for CdA, which could allow the mine to increase TSF reclaim rate, reduce fresh-water make-up requirement and locally produce electricity. Similarly, the evaluation indicates that HVC would greatly benefit from enhanced pit dewatering in order to reduce the current and future operational impacts caused by the presence of groundwater in the pits. For QB2, the construction of a land-based solar plant was the only potential option identified for the project, which could potential partially offset the high power costs. However, this option would require significant investment and is not deemed recommendable due to the current capital intensive nature of the project. Finally, the preliminary gap analysis completed indicates that the relative difference between current versus intended water management practice creates some risks for HVC and CdA. These risks are mostly related to not using the groundwater and TSF reclaim water to their full potential.

6: Conclusions and Recommendations

Mining companies use vast quantities of water primarily for the ore extraction process. Water is a critical resource and the mining industry shares a responsibility to ensure water is available for neighbouring communities today and in the future. In this context, this paper demonstrates the costs related to “wet mining” and water supply for Teck’s HVC, CdA and QB2 open pit mines. Water management options were developed which offer potential opportunities towards sustainable mining.

6.1 Conclusions

This analysis of the lifecycle of water in the mining industry demonstrates that water has significant implications on the operational, financial and sustainability aspects of mine operations. The presence of water in open pits generally increases mining costs primarily due to loss of access, reduced slope performance and a general increase in operating costs. The costs of “wet mining” include lower truck productivity, reduced tire life, higher equipment maintenance costs and increased fuel consumption. For the three Teck mines considered in this paper, THVC is the only site where groundwater in the open pit negatively affects the operation. The financial impact of groundwater on open pit mining operations at THVC is estimated at over $8M/year. This is a significant hit considering that THVC typically spends on average approximately $5M/year on pit dewatering activities. The difference justifies the need for additional pit dewatering measures to minimize the effect of groundwater on mining operations.

Teck’s mineral processing facilities use large amounts of water and power to transform ore rock into copper concentrates. This transformation process generates mine tailings, which are typically disposed of in a tailings impoundment, from where process water is recycled (reclaimed). Since these facilities “lose” water to evaporation and seepage, the missing volume needs to be compensated from other sources, which can be surface or groundwater.

The water reclaim rates estimated in this paper range from 81% at THVC to about 40-74% for the QB2 project and CdA, respectively where evaporation losses are significant. THVC uses on average 1.46m^3 of water per tonne of copper processed, versus 0.89m^3/tonne for QB2. Although HVC shows the highest water-recycling rate, this suggests that site THVC, where water is abundant is somewhat less “efficient” than QB2 and CdA, where the water resource is scarce. The cost of reclaim water varies substantially between mine sites as a function of $/kWh, recycling rate and configuration/efficiency of the reclaim circuit. Unit costs for reclaim water were estimated at $0.11/m^3 for THVC to $0.91/m^3 at CdA. Overall, the annual cost of water supply to the process plant ranges from over $13M/year for CdA, to $20M/year for THVC and over $70M/year for QB2. These costs respectively represent 11%, 5% and 12% of the total production costs for these mine sites.

The sources of make-up water are often located at considerable distances away from the operation, which implies high energy and infrastructure costs to pump water to the desired location. Make-up water for THVC and CdA respectively come from the Thompson River and the Elqui Valley aquifer, both located over 40km away and 1,000m lower in elevation from the mine site. In comparison, make-up water for the QB2 project will be sourced from desalinated water from the Pacific Ocean located over 200km away, and 4.400m lower in elevation from the mine site. As a result, the unit cost ($/m^3) of make-up water is typically 2-5 times that of reclaim water, which in turn can be cheaper than extracting water locally from the mine dewatering system (wells), at least based on the experience at THVC which obtains about 18% of make-up water from pit dewatering activities. For these reasons, maximizing reclaim water and minimizing make-up water requirements should be a priority for Teck in order to reduce operating costs related to water. In this regards, the optimization of open pit dewatering activities at THCV is considered a necessity to maximize the contribution to make-up water (i.e. minimize Spatsum) while at the same time reducing operational impacts in the open pits.

Beyond the considerable financial implications, make-up water extraction also creates sustainability challenges in terms of community relations (often competing for the same water resource), energy and material stewardship. Water regulations towards the mining industry are currently changing in British Columbia, along with the management of Tailings Storage Facilities. Since BC is considered a world mining leader, it is fair to assume that other mining jurisdictions such as Chile will soon follow the course. These changes imply that water extraction will become more costly and more restricted, and that mining companies such as Teck will need to adjust in order to reduce production costs to remain competitive. Mining costs are trending upwards as a result of rising energy costs and difficulties in permitting and commissioning new projects, while copper head grades are generally decreasing.

Carmen de Andacollo (CdA) and the Quebrada Blanca Phase 2 expansion (QB2) project are located in water-stressed regions of the Atacama Desert in Chile, where the allocation of water is essential. Demand for water in these regions may result in water resources becoming unavailable or more costly to utilize. These conditions create a risk for Teck related to potential increase in operating and capital costs for water supply, or result in community concerns.

The findings from this project indicate that water is an expensive commodity for mining processes and can also significantly increase operating costs in the mine. However, these costs and impacts have thus far been very poorly quantified not only by Teck. The industry in general needs to appreciate the cost of water in mining, beyond the sustainability implications. Now more than ever during an economic downturn, Teck needs to identify and implement water management strategies and technologies to conserve this critical resource and minimize costs to stay competitive. This project has identified a number of innovative potential options available for Teck to respond to water issues, and assist the company in turning risks into opportunities. Among these options, increased pit dewatering activities present an interesting avenue to provide cheaper make-up water for CdA, and can also improve mining operations and reduce production costs at THVC. Fog water collection and the installation of a floating solar power plant over the TSF were also identified as promising options to supply make-up water and increase reclaim rates more economically for CdA; these options also offer significant sustainability advantages.

Finally, the use of "Best Practice" in TSF management needs to be implemented not only to increase reclaim water recovery but also reduce the liability incurred by tailings dams. Figure 6.1 proposes a modified strategy for Teck to manage the water resource at mine sites, which aims at integrating the optimization elements discussed above.

6.2 Recommendations

Teck needs to develop a deep appreciation of the cost implications of (i) groundwater impacts in an open pit mining environment and (ii) make-up water supply. For all three sites considered in this study (THVC, CdA and QB2), it is necessary for Teck to analyse the lifecycle of water and break down the energy requirements for getting the water from its source to the processing facility. A unit water cost should be defined for each segment of this lifecycle. In addition, the following recommendations are specifically extended for each site considered.

THVC

Develop a tailings deposition plan for the tailings storage facility. HVC should commission an engineering study to develop a tailings disposition plan and define capital investments required to procure the additional infrastructure needed. This plan should involve multiple tailings discharge point to create flexibility in managing the pond. In turn, it is required to ensure a physical connection between the reclaim pumping system and the supernatant pond at all time. The main benefit of developing this plan is to avoid the need of operating the Spatsum Booster station to pump make-up water from the Thompson River to the plant (higher unit cost water) to the processing facility.

Enhance pit dewatering activities. The abundance of groundwater in all three active pits at HVC creates "wet mining" conditions and has a significant impact on mine operations, and consequently on the mining cost per tonne. HVC should increase pit dewatering activities to reduce the operating costs related to water. In addition to the installation of additional dewatering infrastructure, the efficiency of the dewatering system would need to be closely monitored to confirm the intended benefits on mine operations. This is a complex endeavour that involves the tracking of muck water content, maintenance cost, fuel consumption, pumping costs, etc. As such, a focus group should be assembled to quantify the performance of the dewatering effort at reducing costs.

Review reclaim water flow path to reduce energy requirements. Although the unit cost of electricity is relatively low at HVC (compared to Chilean operations), the operations is a large consumer. After years of investment in water flow monitoring instrumentation at key measurement points across the property, HVC now benefits from a reliable water balance and water flow diagram. At this stage, it is recommended to use these tools to review whether the current water reclaim system could be optimized to reduce energy requirements, and subsequently take appropriate actions if areas of improvements are identified.

CdA

Enhance pit dewatering activities to supply make-up water. Teck CdA needs to improve and enhance the current network of pumping wells in the open pit to off-set the high unit cost of make-up water from the lower valley aquifers. The availability and use of availability of existing wells need improvement in an expedite manner. In addition, additional wells should be installed as the pit is advance to maximize groundwater extraction. Further engineering investigation should be carried out to evaluate the maximum groundwater extraction from the pit, which is currently estimated at 100L/s. Surface sumps and pumping infrastructure will need to be upgraded accordingly to match the increased water inflow from the open pit.

Improve water balance and track the cost of water from the mine. The Superintendent of Water Resources currently reports to the Mill Operations Manager at CdA. This group maintains a detailed record of reclaim rate, make-up water production and energy consumption related to these activities. However, open pit dewatering activities are administered by the Mine Operations group, whose goal is to maintain productive operations in the open pit. This group currently does not record the production of groundwater from the mine, energy consumption and pumping costs to the same level as the “Water” group. Therefore, it is recommended that all water functions be under the responsibility of the Water group to harmonize water management activities, i.e. from the water balance to all costs related to water from the mine.

Commission a conceptual study for floating solar plant at the TSF. The water reclaim rate at CdA is impacted by high evaporation rate. This situation, combined with a moderate contribution of pit dewatering to the make-up water balance places a high demand from make-up water from the Elqui River aquifers. The unit cost of this water is estimated at $1.44/m^3 mainly due to the high energy requirement and unit costs related to pumping it to the plant site. Teck CdA should commission a conceptual study to formally evaluate the feasibility and economics for constructing a floating solar plant to cover all, or part of the TSF pond. The first advantage of this facility is that it could likely greatly reduce evaporation losses, thus increase reclaim rate and consequently reduce the requirement for make-up water. Secondly, the solar plant could produce on-site electricity at a competitive price.

Commission a conceptual study for fog water collection. Teck CdA should investigate the possibility to take advantage of unique climatic conditions prevailing on the coastal mountain range between the mine site and the city of La Serena. A conceptual study should be commissioned to confirm the potential and economics for constructing a network of large fog collectors (LFCs) at lower elevations. This study would also need to consider the water storage and pumping infrastructure to transport the collected water from the source to the mine site. It is envisioned that this option could offer an opportunity to develop a partnership with the adjacent town of Andacollo, thus favoring the community aspect of Teck's sustainability strategy.

<u>QB2</u>

Fog water collection. Although fog water could not realistically be collected in any amount sufficient to make a material difference to the QB2 water balance, it is a potentially interesting option to provide drinking or common-use water for local communities impacted by the project such as Pintado and Huatacondo. As a first stage, it is recommended that the QB2 engineering team carry out a conceptual level evaluation of the feasibility and economics for the construction of a fog water collection system. Subsequently, the SEIA team should explore the level of interest of these communities to obtain fresh, high quality water in lieu of the current truck-delivered water. It is envisioned this relatively small investment from Teck could be highly beneficial in building and/or improving the relationships with these communities.

Appendices

Appendix A

Table A.1: Summary of annual blast holes re-drill at THVC.

Month/Year	# Redrills	Total Holes	% Redrills
2008 Total	111	25457	0.0044
2009 Total	69	21756	0.0032
2010 Total	33	26761	0.0012
2011 Total	225	31245	0.0072
2012 Total	254	47535	0.0053
5-Year Avg	138.4	30551	0.0043
5-year Max	254	47535	0.0072
Assume 1.5% re-drill (budget value)	458	30551	0.015
Assume 1/2 due to water	229	30551	0.075

Table A.2: Unit cost of drilling and blasting at THVC vs. impact of re-drills

Component	Unit Cost (S CAD)	Unit (per)	Price per hole	Price per re-drill hole
Drilling	12.66	m	208.89	313.34
Explosive	0.431	kg	419.79	419.79
Primer	4.8	each	4.8	4.8
Downline	9.3	each	9.3	9.3
Surface delay	4.07	each	4.07	4.07
Stemming	5.46	hole	5.46	5.46
TOTAL ($ CAD)			**652.31**	**756.76**
Average re-drill cost per year (past 5 years)			$/yr	98,489.47
Max re-drill cost per year (past 5 years)			$/yr	170,270.78
Average toness per hole			T	2,050
Average additional cost per tonne			$/T	0.051
Average tonnes per year re-drill			T/yr	266,800
Max tonnes per year re-drill			T/yr	461,250
Note:				
16.5	average hole depth (m)			
974	average charge weight (kg)			

Drilling and blasting: The incremental costs for drilling and blasting are:

1. If the pattern is wet, it can take 25-50% longer time to access the pattern and to drill it
2. Re-drill costs due to water
3. Increase in costs due to slower loading (perhaps 3 times as long to load wet holes)
4. Use of more expensive ammonium nitrate slurry for wet holes, instead of anfo?
5. The need for higher detonation power – water adds 30% to detonation costs

Table A3: Budget 2013 mining operating cost at THVC.

COST									
PERIOD	Q1-15	Q2-15	Q3-15	Q4-15	2016	2017	2018	2019	2020
Operators Required	191	191	191	191	182	184	188	191	182
Operator Cost	$ 4,909,072	$ 5,134,776	$ 5,191,262	$ 5,360,480	$ 19,678,827	$ 19,840,720	$ 20,272,040	$ 20,595,530	$ 19,678,827
Consumables									
Diesel	$ 12,275,136	$ 12,825,231	$ 13,676,066	$ 14,338,165	$ 51,342,046	$ 50,744,877	$ 51,458,629	$ 54,479,674	$ 51,017,792
Lubricants	$ 1,271,454	$ 1,328,270	$ 1,344,438	$ 1,387,959	$ 5,100,223	$ 5,131,588	$ 5,240,838	$ 5,336,862	$ 5,027,749
Tires	$ 2,595,553	$ 2,711,539	$ 2,744,544	$ 2,833,387	$ 10,411,623	$ 10,475,672	$ 10,698,671	$ 10,894,699	$ 10,263,675
Total Consumables Cost	$ 16,142,143	$ 16,865,040	$ 17,165,047	$ 18,551,511	$ 66,853,894	$ 66,352,147	$ 67,398,136	$ 70,711,234	$ 66,309,215
Total Operations Cost	$ 21,051,214	$ 21,999,816	$ 22,356,249	$ 23,911,991	$ 86,532,721	$ 86,192,867	$ 87,670,176	$ 91,306,764	$ 85,988,043
Maintenance Labour Cost	$ 1,894,703	$ 1,981,816	$ 2,003,594	$ 2,068,929	$ 10,760,609	$ 9,451,200	$ 6,714,559	$ 9,965,936	$ 8,479,607
Maintenance Material Cost	$ 5,260,727	$ 5,502,600	$ 5,563,068	$ 5,744,472	$ 29,877,312	$ 26,241,680	$ 18,643,274	$ 27,670,867	$ 23,544,008
Total Maintenance Cost	$ 7,155,430	$ 7,484,415	$ 7,566,662	$ 7,813,401	$ 40,637,921	$ 35,692,880	$ 25,357,833	$ 37,636,803	$ 32,023,615
TOTAL COST	28,206,644	29,484,231	29,922,911	31,725,392	127,170,642	121,885,747	113,028,008	128,943,567	118,011,657
$ / Hr	376	376	377	387	422	402	365	409	398
$ / Tn	2.40	2.43	2.49	2.55	2.52	2.36	2.18	2.50	2.33

COST							
PERIOD	2021	2022	2023	2024	2025	2026	2027
Operators Required	160	113	116	139	138	120	128
Operator Cost	$ 17,252,800	$ 12,184,790	$ 12,508,280	$ 15,029,434	$ 14,880,540	$ 12,939,600	$ 5,211,291
Consumables							
Diesel	$ 44,603,483	$ 32,119,054	$ 34,652,631	$ 41,821,593	$ 41,604,900	$ 35,484,796	$ 14,425,429
Lubricants	$ 4,408,449	$ 3,171,059	$ 3,270,620	$ 3,876,576	$ 3,830,459	$ 3,270,966	$ 1,313,609
Tires	$ 8,999,432	$ 6,473,416	$ 6,676,062	$ 7,913,663	$ 7,819,520	$ 6,677,372	$ 2,681,609
Total Consumables Cost	$ 58,011,364	$ 41,763,529	$ 44,599,314	$ 53,611,831	$ 53,254,879	$ 45,433,136	$ 18,420,646
Total Operations Cost	$ 75,264,164	$ 53,948,319	$ 57,107,594	$ 68,641,265	$ 68,135,419	$ 58,372,736	$ 23,631,937
Maintenance Labour Cost	$ 7,428,700	$ 7,740,340	$ 4,675,234	$ 8,164,642	$ 7,897,066	$ 5,726,394	$ 2,135,586
Maintenance Material Cost	$ 20,626,118	$ 21,491,402	$ 12,980,995	$ 22,669,495	$ 21,926,557	$ 15,899,589	$ 5,929,549
Total Maintenance Cost	$ 28,054,818	$ 29,231,742	$ 17,656,229	$ 30,834,138	$ 29,823,623	$ 21,625,983	$ 8,065,135
TOTAL COST	103,318,982	83,180,061	74,763,822	99,475,403	97,959,041	79,998,718	31,697,072
$ / Hr	397	444	387	435	433	414	409
$ / Tn	2.01	1.68	1.61	2.07	2.11	1.79	1.95

Note: THVC assumes 2% water content by weight for budgeting.

Table A4: Estimated cost impact of water-related inefficiency at THVC (using 2013 budget values).

Assumed Hauling Inefficiency during Wet Periods:		**15%**
Average unit cost of hauling	$/T	2.4
Increase unit cost for inefficient hauling	$/T	2.76
Incremental unit cost for inefficient hauling	$/T	0.36
Average truck productivity	TPOH	400
Number operating hours per day	hour	22
Incremental daily cost per truck, wet period	$/day	3,168
Average fleet per day	trucks	38
Incremental hauling cost, wet period	$/day	120,384
4 weeks of wet conditions per year	$	3,370,752

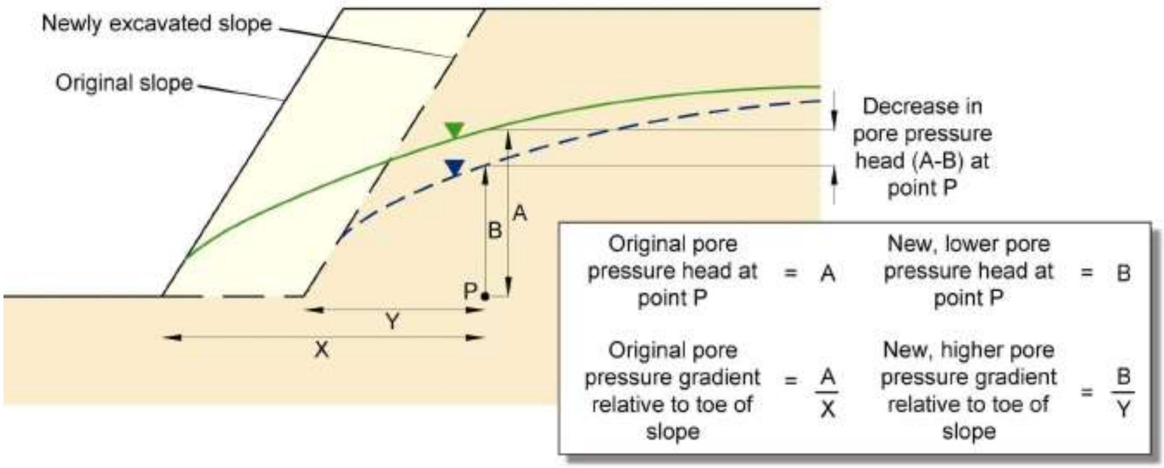
Note: The assumption used of 4 weeks per year of wet operating conditions due to presence of groundwater is considered to be conservative and would need to be further quantified, as the cost implication might be significantly greater than shown on Table 4.

Table A5: Estimated CO2 emission impact of wet hauling at THVC

Consider CAT 793C haul truck			Hauling Conditions	
			Good	Bad
Enginee load factor		%	30	40
Best truck ratio index		-	1.761	2.23
Diesel fuel consumption		L/hr	200	245
CO2 production		T/hr	0.534	0.654
Extra fuel consumption	per truck	L/day	990	@ 22hrs/day
	per fleet	L/day	37,620	@ 22hrs/day
	per truck	L/year	27,720	@ 28days/yr
	per fleet	L/year	1,053,360	@ 28days/yr
Equivalent CO2 emission	per truck	T/year	74	
	per fleet	T/year	2,812	
Note: Using EPA's value of 2.67kg/L diesel.				

http://www.ret.gov.au/energy/Documents/energyefficiencyopps/res-material/Analysis-of-Diesel-Use.pdf

Figure A.6: Impact of dewatering/depressurization on piezometric surface. (from G. Beale, September 2011)



Appendix B

Comparative Case Study – Collahuasi Mine (1990)

(from G. Beale, Principal Hydrogeologist, SWS, pers. Comm., October 11, 2013)

Some of the potential cost savings associated with an expanded dewatering system are as follows:

- *Drilling and blasting costs*. The incremental cost for a wet blast hole in Collahuasi is approximately $178 (made up of $153 in additional slurry costs, $15 in additional drilling costs, and $10 in additional hole loading costs). This equates to about $0.048/ton (assuming 3,700 tons of rock per blast hole). Over the next 5 years, assuming that an expanded dewatering system would reduce the percentage of wet blast holes from 50-60% to about 25-30%, potential cost savings may be within the range $7.9-9.5 million.

- *Operating costs*. Operating costs would increase significantly for a wet pit due to 1) increased maintenance and tire costs for the mobile equipment, and 2) the weight of water moved by the haul trucks. Assuming that loading and hauling costs could increase from $0.37 to $0.39 for a wet pit, an expanded dewatering system may lead to additional cost savings of about $13 million over the next 5 years.

- *Mining rate*. If the pit were mined wet, a reduction in the overall mining rate could potentially be expected.

- *Pit slope considerations*. If the pit were mined wet, pore pressures in the pit walls would not dissipate at the same rate, and the risk of slope failure would potentially increase for some sectors of the pit.

<u>Other comments</u>: (from G. Beale, pers. Comm., October 11, 2013)

For a mine with hard, low porosity rock, the moisture content of dry intact rock would be less than 0.1% and the moisture content for wet intact rock would be 1-2%. The normal post-blast porosity for hard rock is 6-10% (….there are probably some literature values for porosity of shot muck, so you might want to do a quick google search to define a range). For a dry blast, there would be minimal recharge from the zones surrounding the blast, so the total moisture content would stay at less than 0.1%. For a wet blast, the blast would drain the surrounding intact zones and there would be on-going recharge, so we can assume a post-blast moisture content of 2-4%, depending on the site specific conditions. The post-blast moisture content could be 10% if water was running directly into the shot muck. For rock types that have a higher intact porosity, the difference in moisture content between “dry” and “wet” rock would be higher, there would be more water available, and the difference in post-blast moisture content would be greater.

From a material stewardship viewpoint relative to explosives, the Newmont’s Ahafo mine, Ghana provides an example where no/low ammonia in the dewatering wells and very high ammonia in the sump waters. Because they do not run an efficient dewatering wells system, they might have to build a treatment plant specifically from ammonia. I always say that slope depressurization has a 5:1 return – for every $1 you spend on depressurizing the slope you get $5 return in terms of better slope angles and/or improved performance.

Appendix C

Qualitative mine maintenance impact of wet mining at THVC
(from D. Adema, Superintendent Mine Maintenance, HVC, pers. Comm., October 17, 2013)

I do not have much in the way of a quantitative response, but I can list a few ways that wet conditions hurt us.

- Wet roads substantially increase the cutting of tires
- Grader operating hours required increase in wet weather
- In extreme conditions, we have frame cracking issues. This was the case during while excavating the 10B's.
- Wet muck builds up in the dump bodies. The effect on productivity is obvious, but this also tends to result in overloading of trucks, which can in turn lead to frame cracking, reduced life of tires and major components including engine, transmission, differentials and final drives.
- Conditions like what we're currently facing at 18 shovel cause strain and reduced on propel transmissions, drive tumblers and tracks.
- Undercarriage life is reduced in muddy conditions.
- Trailing cable failures!
- Light vehicle maintenance increases substantially in wet conditions (spring and fall), particularly brakes and wiring issues.

Appendix D

Table D.1: Selected water and energy consumption data for HVC

Valley DW	Line A	0.427	$/m^3$	5.8	kWh/m^3$	
(source: Rojas, 2012)	Line B	0.379	$/m^3$	5.15	kWh/m^3$	
	Line C	0.455	$/m^3$	6.18	kWh/m^3$	
	Line D	0.579	$/m^3$	7.86	kWh/m^3$	Groundwater
Highmont	Wells	0.315	$/m^3$	4.29	kWh/m^3$	
Lornex	Wells	0.219	$/m^3$	2.97	kWh/m^3$	
Shula Flats	Wells	0.28	$/m^3$	3.77	kWh/m^3$	
Average	Wells	0.38	$/m3			
Reclaim	HH dam	0.105	$/m^3$	1.43	kWh/m^3$	
Bethsaida	Sumps	0.169	$/m^3$	2.3	kWh/m^3$	Surface Water
Make-up	T. River - Spatsum	0.566	$/m^3$	7.68	kWh/m^3$	
				47.43	kWh/m^3$	
Electricity Consumption 2010		892,966,596	kWh			
Electricity Consumtion (for water)		647,933,273	kWh			
Water Consumption 2010		71,899,117	m^3			
Reclaim water (81%)		58,238,285	m^3			
Make-up water 2010		13,660,832	m^3			
Unit rate of electricity		0.031	$/kWh			
Annual Energy Cost - electricity		20,137,766	$/yr			
Unit water Cost per year		0.280	$/m^3$			

Table D.2: Selected water and energy consumption data for QB2 (source: Teck, 2012)

1. Make-up water			
Energy Requirement	341,914	MWh/yr	Annual Energy Consumption
	341,914,000	KWh/yr	Annual Energy Consumption
	0.115	$/kWh	Unit rate of electricity QB2
	$ 39,320,110	$/yr	Electrical cost per year - OPEX
Make-up water requirement	3500	m3/hr	Operating average
	84000	m3/day	Daily water consumption
	30,660,000	m3/yr	Annual Water consumption
	1.28	$/m3	Desalineated water - Unit pumping cost
Sea water treatment	$ 32,930,000	$/yr	Desalineater water - OPEX
	$ 1.07	$/m3	Desalineated water - Unit treatment cost
TOTAL MAKE-UP Water	$ 2.36	$/m3	Total unit cost of make-up water from Pacific Ocean
2. Reclaim water			
Energy Requirement	65,969	MWh/yr	Annual Energy Consumption
	65,969,000	KWh/yr	Annual Energy Consumption
	0.115	$/kWh	Unit rate of electricity QB2
	$ 7,586,435	$/yr	Electrical cost per year - OPEX
Reclaim water requirement	1500	m3/hr	Operating average
	36000	m3/day	Daily water consumption
	13,140,000	m3/yr	Annual Water consumption
	0.58	$/m3	Reclaim water - Unit pumping cost

Appendix E

CURRENT PRACTICE (THVC) GROUNDWATER MANAGEMENT			Focusing Question: How well does this mine site manage groundwater?									
Item		Additional Context	Current Practice		Target Level Of Practice		Nothing or Not Applicable	Minimum Practice or Operational Requirement	Standard Practice		Industry Best Practice	Leading Practice and Innovation Opportunities
									Below average	Average		
			Rank	Comments	Rank	Comments	0	1	2	3	4	5
1.01	Financial impact of groundwater to open pit mine operations	Is groundwater negatively impacting mining operations? What is the relative or approximate annual costs related to presence of groundwater?	**3**	Multi-million $ annual impact of groundwater to mine operations. The mine deals with it to a level just sufficient to maintain operation.	**4**	Level 4 needed to reduce financial impact	No financial impact	There probably is some impact but extent is not known or measured. Impact likely not very high.	The site knows groundwater is impacting operations but does little to remediate to the situation. Substantial impact but taken as a hit.	Impact of groundwater is acknowledge and quantified to a certain degree. Some actions taken to reduce the impact.	***Role and impact of groundwater on the mine is known and at all levels of the organization, and all measures taken to mitigate the impact.***	Groundwater is controlled and seen as an opportunity to the mine.
1.02	Annual spending levels to remediate to operational impact	Is there an annual budget and/or plan in place to mitigate the operational impact of groundwater in the mine	**3**	Full-time engineering personnel at site; however, the site-based senior geotechnical role is currently vacant.	**4**	Targeting Level 4 to reduce mining costs	No cost or no need to spend	Nominal annual amount included in the budget or as a G&A item.	Some budget created but not alligned with the impact of groundwater on operations	Formal annual budget in place and part of planning cycle. Spendings commensurate with relative impact to the mine.	***Spendings on groundwater are aligned with impact to mine operations and well understood to optimize mining costs***	Impacts of groundwater on the mine are well understood and drive the budget planning cycle to optimize the mine
1.03	Groundwater potential for site make-up water	What is the potential of open pit groundwater to supply the process plant? (high-medium-low). Is this potential exploited?	**3**	Abundance of groundwater which is collected adequately to serve the process plant	**4**	Level 4 is targeted to optimize the flow process of the water collected, i.e. to reduce energy costs	No potential	Minimum potential, or no use of that potential	Some potential, but minimum use of that potential	Formal annual budget in place and part of planning cycle. Spendings commensurate with relative impact to the mine.	***Potential is well defined and understood. The site is exploiting the groundwater resources at its optimum.***	Site making use of latest technology and practice, or defining practice. Lowering units costs and efficiencies.
1.04	Reliabability of open pit (s) water balance	Do we have a water balance for the site and/or for the open pit? How reliable is it?	**3**	Judged to currently be at Level 3, missing instrumentations in some areas.	**5**	Level 5 is judged to be necessary. The impact of groundwater and energy requirements to manage the water are substantial.	No water balance existing, or no groundwater.	Only keeping track of open pit contribution to process plant. No instrumentation in the pit.	Existence of basic water balance, several assumptinos made due to lack of instrumentation.	Develpoment of a pit water balance. Some instrumentation in place. Pit inflows and outflows accurately measured ad-hoc.	Reliable groundwater balance. Pit inflows and outflows accurately measured on a fixed schedule. Water balance model updated annually.	***Water balance periodically reviewed in-house or 3rd party review, timely support from consultants when required, site is an industry reference. Efficient flow path from an energy perspective.***
1.05	Cost tracking of groundwater	Do we know the unit cost of water on site? Is there someone keepting track of power and water costs?	**2**	Nobody keeps track of groundwater costs and/or systems efficiencies at THVC. It is a G&A item in the mine annual budget.	**3**	As a minimum starting basis, THVC should keep track of water related cost on an annual basis, and eventually target Level 4.	No cost implication or no groundwater.	Presence of some groundwater and cost implication, but not cost tracking.	Groundwater cost implication is known but only dealt with as a G&A item for the mine budget. Nobody tracking the costs.	***Existing high level understanding of performance, efficiencies of the dewatering system and of unit costs of water on an annual basis.***	Water-related costs are well-understood and tracked on a monthly basis to optimize systems.	Water-related costs are well understood and used to develop mine operation and development strategies.
1.06	On-site expertise and capacity/availability of groundwater-related personel	Do we have people on site (staff and/or contractors) to assess and manage the groundwater situation	**3**	Dewatering activities are managed by the Mine Engineering and Mine Operations group, generally pro-actively	**5**	Level 5 should targeted considering the volumes of groundwater involved, energy requirements and future expansions	No need or nobody on site	Nobody on site, but minimal involvement from consultant	Need for some on-site personel to manage the situation but personel either not qualified or staffing level insufficient	On-site personel qualified and staffing level allowing to barely keep up with situation requirements	Formal pit dewatering group on-site managing all water aspects	***Pit dewatering group integrated with mine planning/budgeting/energy groups***
1.07	Groundwater impact to geotechnical stability of open pit slopes	Does the presence of groundwater impact the stability of pit slopes, or do we know?	**4**	Geotechnical assessments are updated for all pits	**4**	Level 4 likely sufficient for now	No impact	Probably no impact, we don't know	Previous experience suggest that groundwater may impact the pit walls, but no recent studies completed	Some recent geotechnical evaluation carried out to confirm impact of groundwater on pit slopes stability	***Frequent and updated assessment of impact of groundwater on pit wall stability. Studies completed prior to and during mining.***	Geotechnical and hydrogeological assessment carried out together to optimize pit designs and lower mining costs.
1.08	Environmental and/or communities challenges	Are we competing with other users for groundwater near the mine site? Are we or could we (be) impacting others?	**4**	THVC is a leader in communities involvement with respect to water resources.	**4**	Level 4 is judged to be sufficient.	Not applicable, or no issue	Potential interference with neighbors considered but not formally addressed	Reactive assessment of potential impact of groundwater extraction on surrounding communities	Pro-active assessment of potential impact of groundwater extraction on surrounding communities	***Groundwater management plans developed in conjunction with surrounding communities.***	Groundwater management plan is developed to improve financial returns of the mine and/or sustainability of the operation

CURRENT PRACTICE (CdA) GROUNDWATER MANAGEMENT			Focusing Question: How well does this mine site manage groundwater?									
Item		Additional Context	Current Practice		Target Level Of Practice		Nothing or Not Applicable	Minimum Practice or Operational Requirement	Standard Practice		Industry Best Practice	Leading Practice and Innovation Opportunities
									Below average	Average		
			Rank	Comments	Rank	Comments	0	1	2	3	4	5
1.01	Financial impact of groundwater to open pit mine operations	Is groundwater negatively impacting mining operations? What is the relative or approximate annual costs related to presence of groundwater?	3	Impact on operations is minimal but well managed	3	Level 3 is adequate for now	No financial impact	There probably is some impact but extent is not known or measured. Impact likely not very high.	The site knows groundwater is impacting operations but does little to remediate to the situation. Substantial impact but taken as a hit.	***Impact of groundwater is acknowledge and quantified to a certain degree. Some actions taken to reduce the impact.***	Role and impact of groundwater on the mine is known and at all levels of the organization, and all measures taken to mitigate the impact.	Groundwater is controlled and seen as an opportunity to the mine.
1.02	Annual spending levels to remediate to operational impact	Is there an annual budget and/or plan in place to mitigate the operational impact of groundwater in the mine	1	Although the budget is in place, the availability and use of availability of existing wells are low	3	Level 3 is deemed required to make use of existing dewatering infrastructure	No cost or no need to spend	Nominal annual amount included in the budget or as a G&A item.	Some budget created but not alligned with the impact of groundwater on operations	***Formal annual budget in place and part of planning cycle. Spendings commensurate with relative impact to the mine.***	Spendings on groundwater are aligned with impact to mine operations and well understood to optimize mining costs	Impacts of groundwater on the mine are well understood and drive the budget planning cycle to optimize the mine
1.03	Groundwater potential for site make-up water	What is the potential of open pit groundwater to supply the process plant? (high-medium-low). Is this potential exploited?	3	Dewatering wells in placed but not optimized	4	Level 4 is targeted to extract as much groundwater as possible	No potential	Minimum potential, or no use of that potential	Some potential, but minimum use of that potential	Formal annual budget in place and part of planning cycle. Spendings commensurate with relative impact to the mine.	***Potential is well defined and understood. The site is exploiting the groundwater resources at its optimum.***	Site making use of latest technology and practice, or defining practice. Lowering units costs and efficiencies.
1.04	Reliability of open pit (s) water balance	Do we have a water balance for the site and/or for the open pit? How reliable is it?	3	Existing model is based on assumption since some flow-meters are missing	4	Level 4 is required to develop a reliable water balance, which is needed due to the high cost of water	No water balance existing, or no groundwater.	Only keeping track of open pit contribution to process plant. No instrumentation in the pit.	Existence of basic water balance, several assumptinos made due to lack of instrumentation.	Develpoment of a pit water balance. Some instrumentation in place. Pit inflows and outflows accurately measured ad-hoc.	***Reliable groundwater balance. Pit inflows and outflows accurately measured on a fixed schedule. Water balance model updated annually.***	Water balance periodically reviewed in-house or 3rd party review, timely support from consultants when required, site is an industry reference. Efficient flow path from an energy perspective.
1.05	Cost tracking of groundwater	Do we know the unit cost of water on site? Is there someone keeping track of power and water costs?	2	Nobody keeps track of groundwater costs and/or systems efficiencies at CdA. It is a G&A item in the mine annual budget.	4	As a minimum starting basis, CdA should keep track of water related cost on an annual basis, and eventually target Level 4.	No cost implication or no groundwater.	Presence of some groundwater and cost implication, but not cost tracking.	Groundwater cost implication is known but only dealt with as a G&A item for the mine budget. Nobody tracking the costs.	Existing high level understanding of performance, efficiencies of the dewatering system and of unit costs of water on an annual basis.	***Water-related costs are well-understood and tracked on a monthly basis to optimize systems.***	Water-related costs are well understood and used to develop mine operation and development strategies.
1.06	On-site expertise and capacity/availability of groundwater-related personel	Do we have people on site (staff and/or contractors) to assess and manage the groundwater situation	3	Existing water group but not integrated with pit dewatering activities.	4	Level 4 should targeted to encompass all water on site, including the mine	No need or nobody on site	Nobody on site, but minimal involvement from consultant	Need for some on-site personel to manage the situation but personel either not qualified or staffing level insufficient	On-site personel qualified and staffing level allowing to barely keep up with situation requirements	***Formal pit dewatering group on-site managing all water aspects***	Pit dewatering group integrated with mine planning/budgeting/energy groups
1.07	Groundwater impact to geotechnical stability of open pit slopes	Does the presence of groundwater impact the stability of pit slopes, or do we know?	4	Geotechnical assessments are updated for all pits	4	Level 4 likely sufficient for now	No impact	Probably no impact, we don't know	Previous experience suggest that groundwater may impact the pit walls, but no recent studies completed	Some recent geotechnical evaluation carried out to confirm impact of groundwater on pit slopes stability	***Frequent and updated assessment of impact of groundwater on pit wall stability. Studies completed prior to and during mining.***	Geotechnical and hydrogeological assessment carried out together to optimize pit designs and lower mining costs.
1.08	Environmental and/or communities challenges	Are we competing with other users for groundwater near the mine site? Are we or could we (be) impacting others?	4	CdA is a leader in communities involvement with respect to water resources.	4	Level 4 is judged to be sufficient.	Not applicable, or no issue	Potential interference with neighbors considered but not formally addressed	Reactive assessment of potential impact of groundwater extraction on surrounding communities	Pro-active assessment of potential impact of groundwater extraction on surrounding communities	***Groundwater management plans developed in conjunction with surrounding communities.***	Groundwater management plan is developed to improve financial returns of the mine and/or sustainability of the operation

CURRENT PRACTICE (THVC)

TSF Water MANAGEMENT

Focusing Question: How well does this mine manage the water from the tailings storage facility?

Item		Additional Context	Current Practice		Target Level Of Practice		Nothing or Not Applicable	Minimum Practice or Operational Requirement	Standard Practice		Industry Best Practice	Leading Practice and Innovation Opportunities
									Below average	Above average		
			Rank	Comments	Rank	Comments	0	1	2	3	4	5
2.01	Reclaim rate from the TSF	Are we monitoring reclaim rate? How do we compare with the industry	**4**	THVC's reclaim rate about 80%. Given the size of the impoundment.	**4**	Level 4 considered adequate. Given the size of the TSF, limited potential for alternate technologies.	No reclaim	Not monitoring reclaim rate, or reclaim rate <25%	Reclaim rate below 50% and/or reclaim volumes estimated.	Reclaim rate between 50-70%. Reclaim volume accurately measured.	***Reclaim rate >70%. The operation manages the TSF extremely well and operates nearly in closed-circuit.***	Use of complementary technologies to improve reclaim water system and/or derive value from the TSF.
2.02	Water balance for the TSF	Do we have a water balance for the TSF? Is it reliable?	**4**	THVC has a reliable water balance in place, calibrated with GoldSim model.	**5**	Level 5 is recommended in order to use the available model for predictive scenarios in a pro-active manner to identify future potential upside and/or risks.	No water balance for TSF	Existing poor water balance for TSF, or under development	Water balance in place but based mostly on assumptions due to lack of instrumentation and/or measurement points	Reliable water balance in place, based on adequate instrumentation network. On-site climate monitoring.	Reliable water balance in place, predictive modeling possible by GoldSim or equivalent model. Water balance audited by 3rd party. Monthly measurement of pond volume.	***As for "Industry Best Practice", plus systematic assessments are performed as appropriate based on the asset assessed risk to the Business. Any deficiencies are documented and corrected quickly with learnings integrated into future work.***
2.03	Seepage from the TSF	Are we monitoring seepage? Are we intercepting seepage?	**4**	Formal monitoring station and plan in place, with specific monthly and annual KPIs.	**4**	Level 4 is judged to be sufficient.	No seepage, or no seepage monitoring	Seepage is identified, but no action plan to monitor or address it.	Some sort of diversion of interception structure in place to measure or quantify the seepage.	Measurement , collection and reporting of TSF seepage.	***Monthly measurement, collection and reporting of TSF seepage and comparison against target KPIs.***	
2.04	Tailings disposition plan	Do we have a tailings disposition plan? Is it being followed?	**1**	The TSF is operated with a single discharge point, seriously limiting the ability to manage the pond. No formal annual disposition plan in place. As a result, it may be necessary to use the Spatsum pump house for freshwater make-up.	**4**	Level 4 is deemed necessary in order to ensure sustained, reliable access between the pond and the reclaim pumping system.	No plan, or no need for a plan	No annual plan in place. Tailings disposition plan field-fitted based on operational performance of beaches and pond.	Deposition plan in place, but not updated with water balance or performance of TSF pond and beaches.	Deposition plan in place using multiple discharge points. The plan is updated every few years depending on TSF performance against the plan.	***Proactive modification of deposition plan based on performance. Systematic annual update of deposition plan in sync with water balance.***	
2.05	Evaporation loss	Do we measure evaporation loss? Do we try to minimize it?	**2**	On-site climate station measuring evaporation data on a daily basis. Total evaporation losses estimated on an annual basis as part of the water balance update.	**3**	Level 3 is recommended once a deposition plan has been developed for the TSF.	No evaporation, or no monitoring	Evaporation quantified but not regularly measured. No specific action taken to minimize or reduce evaporation losses.	Evaporation losses estimated annually. No specific action taken to minimize or reduce it.	***Evaporation losses estimated monthly and compared against predictions and deposition plan. Operation of TSF modified to respect plan as needed.***	Detailed monitoring of pond conditions and monthly estimation of evaporation losses. TSF is managed efficiently to systematically minimize the footprint of pond and/or wet beaches.	As for "Industry Best Practice", plus use of complementary technologies to minimize evaporation losses.
2.06	Cost of reclaim water	How do we compare to the industry?	**4**	Reclaim cost of about $0.11/m3, very low due to low cost of hydroelectricity.	**5**	Level 5 is recommended to minimize energy consumption considering the long distance between the LL dam and the plant.	Not evaluated	Between $0.75-$1.00/m3	Between $0.50-$0.75/m3	Between $0.25-$0.50/m3	Below $0.25/m3	***As for "Industry Best Practice", plus optimization of water flow diagram to minimize energy consumption.***

CURRENT PRACTICE (CdA)

TSF Water MANAGEMENT

Focusing Question: How well does this mine manage the water from the tailings storage facility?

Item		Additional Context	Current Practice		Target Level Of Practice		Nothing or Not Applicable	Minimum Practice or Operational Requirement	Standard Practice		Industry Best Practice	Leading Practice and Innovation Opportunities
									Below average	Above average		
			Rank	Comments	Rank	Comments	0	1	2	3	4	5
2.01	Reclaim rate from the TSF	Are we monitoring reclaim rate? How do we compare with the industry	**2**	CdA water reclaim rate of about 46%. Good monitoring in place.	**3**	Level 3 is recommended given the high cost of make-up water.	No reclaim	Not monitoring reclaim rate, or reclaim rate <25%	Reclaim rate below 50% and/or reclaim volumes estimated.	***Reclaim rate between 50-70%. Reclaim volume accurately measured.***	Reclaim rate >70%. The operation manages the TSF extremely well and operates nearly in closed-circuit.	Use of complementary technologies to improve reclaim water system and/or derive value from the TSF.
2.02	Water balance for the TSF	Do we have a water balance for the TSF? Is it reliable?	**3**	CdA has a water balance but still lacking some instrumentation to provide reliable data, to further calibrate with GoldSim model.	**5**	Level 5 is recommended due to the high costs of water at CdA.	No water balance for TSF	Existing poor water balance for TSF, or under development	Water balance in place but based mostly on assumptions due to lack of instrumentation and/or measurement points	Reliable water balance in place, based on adequate instrumentation network. On-site climate monitoring.	Reliable water balance in place, predictive modeling possible by GoldSim or equivalent model. Water balance audited by 3rd party. Monthly measurement of pond volume.	***As for "Industry Best Practice", plus systematic assessments are performed as appropriate based on the asset assessed risk to the Business. Any deficiencies are documented and corrected quickly with learnings integrated into future work.***
2.03	Seepage from the TSF	Are we monitoring seepage? Are we intercepting seepage?	**3**	Formal monitoring station and plan in place.	**4**	Level 4 is recommended to include monthly KPIs to ensure maximum recovery given the low availability of interception wells.	No seepage, or no seepage monitoring	Seepage is identified, but no action plan to monitor or address it.	Some sort of diversion of interception structure in place to measure or quantify the seepage.	Measurement , collection and reporting of TSF seepage.	***Monthly measurement, collection and reporting of TSF seepage and comparison against target KPIs.***	
2.04	Tailings disposition plan	Do we have a tailings disposition plan? Is it being followed?	**3**	CdA uses 7 discharge points as part of a detailed deposition plan.	**4**	Level 4 is recommended to minimize the footprint of pond and wet beaches.	No plan, or no need for a plan	No annual plan in place. Tailings disposition plan field-fitted based on operational performance of beaches and pond.	Deposition plan in place, but not updated with water balance or performance of TSF pond and beaches.	Deposition plan in place using multiple discharge points. The plan is updated every few years depending on TSF performance against the plan.	***Proactive modification of deposition plan based on performance. Systematic annual update of deposition plan in sync with water balance.***	
2.05	Evaporation loss	Do we measure evaporation loss? Do we try to minimize it?	**2**	On-site climate station measuring evaporation data on a daily basis. Total evaporation losses estimated on an annual basis as part of the water balance update.	**3**	Level 3 is recommended once a deposition plan has been developed for the TSF.	No evaporation, or no monitoring	Evaporation quantified but not regularly measured. No specific action taken to minimize or reduce evaporation losses.	Evaporation losses estimated annually. No specific action taken to minimize or reduce it.	***Evaporation losses estimated monthly and compared against predictions and deposition plan. Operation of TSF modified to respect plan as needed.***	Detailed monitoring of pond conditions and monthly estimation of evaporation losses. TSF is managed efficiently to systematically minimize the footprint of pond and/or wet beaches.	As for "Industry Best Practice", plus use of complementary technologies to minimize evaporation losses.
2.06	Cost of reclaim water	How do we compare to the industry?	**1**	Reclaim costs very high at CdA at \$0.90/m3 due to high cost of electricity and operating cost of pumping infrastructure.	**2**	Level 2 is recommended as a minimum, which is achievable with implementation of cheaper reclaim infrastructure and potential generation of on-site electricity.	Not evaluated	Between \$0.75-\$1.00/m3	***Between \$0.50-\$0.75/m3***	Between \$0.25-\$0.50/m3	Below \$0.25/m3	As for "Industry Best Practice", plus optimization of water flow diagram to minimize energy consumption.

Bibliography

AMEC (2008). *Compania Minera Carmen de Andacollo, Proyecto Hipogeno Ingenieria – Solicitude de permisos, Segunda Fase de Construccion y Operacion del Deposito de Relaves (Anexo 1).*

AMEC (2013). Site-wide GoldSim Water Balance Model Report, Highland Valley Copper Mine.

Artois (2012). Quebrada Blanca Hypogeno Project – Feasibility Study, Hydrogeological Evaluation in Support of the Slope Stability Analysis, Preliminary Report.

BCME (2014). The New BC Water Sustainability Act – Bill 18, 2014 Legislative Session: 2nd Session, 40th Parliament, Third Reading, Government of British Columbia, http://leg.bc.ca/40th2nd/3rd_read/gov18-3.htm

BCMMPR (2015). Report on Mount Polley Tailings Dam Facility Breach, Independent Expert Engineering Investigation and Review Panel.

Beale, G. (2011). Keynote speaker presentation, "Water and Pit Slopes – How much do we understand?", International Slope Stability Conference, Vancouver, BC.

Beale, G (2013). Personal Communication via email, October 11, 2013.

Beale, G (2015). Personal Communication via email, February 27, 2015.

Chambers, B. (2003). Water Recovery from a Mine in the Atacama Desert, Water in Mining Conference, Brisbane, Australia.

Cochilco (2013)"*Minuta informe - Consumo de agua fresca en la minería del cobre al año 2013*", *Comisión Chilena del Cobre*.

Davies, M., Rice, S. (2004). An alternative to conventional tailings management – dry stack filtered tailings.

DGA (2007). *Boletín Información Pluviométrica, Fluviométrica, Estado de Embalses y Aguas Subterráneas (N° 356 Diciembre 2007).*

2013 *Direccion General del Agua* website – www.dga.cl

Fortin, S. (2013). "The Cost of Wet Mining", BUS689 class assignment, Simon Fraser University, EMBA.

Golder Associates (2012). Quebrada Blanca Phase 2- Tailings Feasibility Study, Choja South Tailings Management Facility Feasibility Report No. 119 215 1004.

Golder Associates (2009). Mine Site Location – Quebrada Blanca Tailings Disposal Options Trade Off Study, submitted to Fluor Chile S.A.

ICMM (2012). Water Management in Mining – Report by Internation Council of Mining and Metals.

Mackenzie and Wood (2015). Metals Costs Benchmarking Report.

Rojas, J.P. (2012). "HVC Water Supply System: Energy Assessment and Opportunities for Improvement", Final Project, CEEN596, University of British Columbia.

Schlumberger Water Services (2015). "*Modelación 3D Feflow Infiltración Depósito de Relaves – Teck Carmen de Andacollo*", Powerpoint Presentation, March 2015, Schlumber Water Services.

Teck (2012). QB2 Feasibility Report, May 25, 2012.

Teck (2013). Sustainability Report, 2013.

Teck (2015a). Adaptability – Teck 2014 Annual Report.

Teck (2015b). *Plan Integrado Gestion del Agua Teck CDA*, January 2015.

Teck (2015c). THVC Draft Integrated Water Management Plan for THVC, February 2, 2015.

Teck (2015d). 2014 Costs Summary, Internal Powerpoint Presentation, March 2015.

Tercera La (2011). "*Minera El Tesoro – Innovacion al servicio de la sociedad y el medio ambiente*", May 20, 2011.

Veillette, M. (2015). Personal Communication via email sent May 20, 2015.

Websites Reviewed

Dirección General de Aguas. Derechos de aprovechamiento de aguas registrados en DGA.

http://www.dga.cl/productosyservicios/derechos_historicos/Paginas/default.aspx (accessed April 5, 2015).

British Columbia Ministry of Environment. Water Sustainability Act.

http://engage.gov.bc.ca/watersustainabilityact/ (accessed April 10, 2015)

Fogquest – Sustainable Water Solutions. Project Information. Past Projects. Chile El Tofo.

http://www.fogquest.org/?page_id=671 (accessed May 9, 2015)

FlowServe Submersible Incline Pumps for Surface Pumping Applications

http://*www.flowserve.com (accessed April 30, 2015)*

ABC News. Australian-first floating solar farm due to begin construction in SA. By Matthew Doran Updated 4 Mar 2015.

http://www.abc.net.au/news/2015-03-05/australian-first-floating-solar-farm-for-sa/6281374 (accessed on May 16, 2015)

ABC News. Solar power plant floating on wastewater hailed for multiple environmental benefits. By Isabella Pittaway. Posted 29 Apr 2015,

http://www.abc.net.au/news/2015-04-29/solar-power-plant-at-jamestown-wastewater-site/6431872 (accessed on May 16, 2015)

ABC News. Sandfire copper-gold mine in Western Australia may have world's largest solar-pv power project built by Juwi.

http://www.abc.net.au/news/2015-02-12/juwi-to-build-solar-plant-at-sandfire-mine-in-wa/6086856 (accessed on May 16, 2015)

Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean. 1.3 Fog Harvesting. Unit of Sustainable Development and Environment General Secretariat, Organization of American States Washington, D.C., 1997.

http://www.oas.org/dsd/publications/unit/oea59e/ch12.htm (accessed May17, 2015)

Rain Water Connection. Everything you need to know – What is rainwater harvesting?

http://www.rainwaterconnection.com/rainwater-harvesting (accessed May 9, 2015)

Saltworks – Advanced water treatment solutions for the world's most demanding applications. Electrochem Reverse-Osmosis (RO).

http://www.saltworkstech.com/electrochem-salt-splitter-ro/ (accessed May 17, 2015)

Infratech Industries. Renewable energies. Floating Solar.

http://www.infratechindustriesinc.com/what-we-do/our-services/renewable-energy/floating-solar/ (accessed May 16, 2015)